Sea Grant

Estuarine and Watershed Monitoring Using Remote Sensing Technology

Present Status and Future Trends

A Workshop Report

Scientific and Technical Advisory Committee

Maryland Sea Grant College

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Chesapeake Bay Program

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Estuarine and Watershed Monitoring Using Remote Sensing Technology

Present Status and Future Trends

A WORKSHOP REPORT

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Sea Grant

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Executive Summary

The Scientific and Technical Advisory Committee (STAC) of the U.S. EPA Chesapeake Bay Program (CBP) and Maryland Sea Grant College (MDSG) jointly sponsored a workshop that was held 7-8 January 2002 in Annapolis, Maryland, entitled *Present Status and Future Trends in Estuarine and Watershed Monitoring using Remote Sensing Technology (Satellite, Airborne,* In-Situ*).* The impetus for the workshop was a recommendation from a STAC review of the CBP monitoring program that suggested the incorporation of remote sensing technologies into current monitoring efforts, including recent advances such as the global view of plant biomass as chlorophyll (*chl-a*) from the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) (Figure 1).

Larry Harding of MDSG/Horn Point Laboratories (HPL), Jonathan Kramer of MDSG and STAC, and Jonathan Phinney of NOAA and STAC served as the coordinators of the workshop. Participants included state and federal resource managers and members of the academic community within the Chesapeake Bay region and outside institutions with specific expertise and interest in remote sensing technology. The workshop was organized into three thematic areas, each represented by a panel of three scientists and a manager. This report summarizes oral presentations, panel discussions, and recommendations of the workshop, including presentations by twelve invited speakers.

Recommendations

This report provides a synopsis of material presented in the workshop on current and future capabilities for remote sensing of estuaries. Clearly, this topic was not covered exhaustively in a workshop of this scale. Rather, the meeting highlighted existing technologies and approaches that have direct bearing on management needs for Chesapeake Bay and that have shown promise when applied to estuarine and coastal waters and the watersheds that border them. Recommendations that emerged in the discussions coalesce into several categories:

- **Expand and Better Integrate *In-situ* Technologies.** *In-situ* technologies have been in use by the scientific community for many years and a variety of high-resolution data products are currently available. Expanding the use of a range of methodologies, from continuous underway sampling to new sensors on buoys, will greatly enhance monitoring capabilities, particularly in tributaries and the shallow reaches of the estuary.

- **Expand the Use of Aircraft and Satellite-based Sensors.** Remote sensing from aircraft and satellite platforms offers great promise to expand synoptic measurements and to examine understudied regions of the Bay. Partnerships with key agencies (NASA and NOAA) and better utilization of multiple data products, many available at no cost, should be pursued.

- **Increase the Use of Landsat Imagery.** Acquisition of Landsat images (e.g., Enhanced Thematic Mapper [ETM] and finer-scale commercial imagery) for the Bay watershed and increased use of processed imagery for specific applications will improve our understanding of changes on several spatial and temporal scales.

- **Improve and Expand Wetlands Mapping.** A variety of existing and new technologies can be used to examine and predict changes in wetlands. Both LIDAR altimetry and multi- and hyperspectral imaging should be pursued.

Introduction

Over twenty-five years ago, the National Aeronautics and Space Administration (NASA), the Environmental Protection Agency (EPA), and the University of Maryland, College Park (UMCP) convened a conference entitled *Application of Remote Sensing to the Chesapeake Bay Region* at the Coolfont Conference Center in Berkeley Springs, West Virginia. The stated goal of the conference was: "...discussing the complex technical and management issues surrounding the application of remote sensing to the Chesapeake Bay area." The conference was held 12-15 April 1977, just prior to the launch of the Coastal Zone Color Scanner (CZCS) late in 1977 and the development of technologies that we now use to study estuarine and coastal waters around the globe.

The keynote speaker for the conference, the Honorable Charles "Mac" Mathias, Jr., U.S. Senator from Maryland, remarked:

> The Chesapeake Bay, our nation's largest estuary, could, within our lifetime, become a dead sea. There is not time left to grope for solutions. With every year that passes, the Bay is diminished. Some day, unless we intercede, the wear and tear will become terminal. We must join together to ensure the health of the Chesapeake Bay as our legacy to the future.

The meeting addressed the following three main questions in the context of "measuring the state of the Bay." (1) What entities should be measured to develop a comprehensive database? (2) How close together should measurements be made in time and space? (3) What should be done with the data? Twenty-five years later, Bay managers and scientists are still asking similar questions. Fortunately, a better understanding of the structure and function of the ecosystem and breakthroughs in computer and sampling technologies have provided managers with better tools with which to address these questions. The commitment to improving the water quality of Chesapeake Bay remains clear. The technologies used to aid our assessments of the state of the ecosystem and to detect changes accompanying management actions have advanced significantly, now including aircraft, satellite, and *in-situ* instruments barely envisioned in 1977. Thus, it is timely to now revisit the questions posed 25 years ago, armed with potential solutions of the present and future as they pertain to Sen. Mathias's admonition to "ensure the health of the Chesapeake Bay."

Management Considerations

Remote sensing, broadly defined to include *in-situ*, aircraft, and satellite instruments, has revolutionized the observation and interpretation of large-scale biological and physical processes in coastal ecosystems. At present, remote sensing is well integrated into the research community, but is less commonly used by resource managers. Managers face a barrier in incorporating remote sensing into ongoing monitoring programs, because of a disconnect between needs and solutions, in developing ways to use new technologies to address management concerns.

Blanche Meeson of NASA posed the question, "Who should drive the process of applying data from remote sensing to management?" We might ask, "Is it incumbent on developers of technology to "sell" it to management or should management seek relevant technological solutions to existing problems?" In a needs-based system, resource managers must first identify problems and then decide whether or not remote sensing is an appropriate tool. To take this step, it is important for the manager to state requirements of resolution and coverage that pertain to a particular problem and to seek

sources of data and information that meet those requirements. This early consideration requires that resource managers become informed about basic attributes of remote sensing platforms and instruments to determine if such an approach is part of a toolbox they might use. Clearly, remote sensing with instruments on aircrafts and satellites is not a solution to all problems, and the use of data and information from these sources should be driven by need rather than by capability. This truism helps identify an important role for those in the research and development community — one that argues for increased collaboration and a commitment to ongoing technology transfer.

Once a potential match of a management need to a remote sensing solution can be identified, several key questions emerge:

- Can data and information from remote sensing move a resource manager significantly toward a solution to a specified problem?

- What are the requirements in spatial and temporal resolution to address a particular need, and how are these matched by data availability?

- Can data be obtained reliably when they are needed and with sufficient coverage in time and space to be useful?

Another consideration is the distinction between operational and research applications. Relevant questions that should be posed to managers in this context are:

- Do you need to be able to acquire a specific measurement reliably every time you go out in the field?

- Do you need sustained measurements over a long period?

These considerations raise other issues, such as the longevity of a desired data set to support long-term monitoring. A long-term need is quite different from the relatively short-term need for data required to support an individual research effort. It is important for managers to specify their needs to assure that calibrated and validated data for a particular product are available over a desired timeframe, particularly in monitoring applications. A research instrument may be deployed for a prescribed period of time, perhaps several years, and as such might not be suitable for managers charged with tracking long-term changes. Although the needs of these researchers and managers may overlap, they are not identical. In order for managers to take advantage of emerging technologies, needs for data set longevity must be weighed carefully.

"Cost" is often an important consideration in deciding whether to obtain and use data from remote sensing. Some important questions are:

- What are the costs to collect and/or to purchase data and to process and reprocess the data for specific needs?

- Will it be necessary to support data archival to enable studies of long-term trends?

A user needs to be able to access data, to sustain a data flow, and to know the data are provided at a quality that makes them useful. There may also be a need for specialized algorithm development if "off-the-shelf" algorithms are not suitable for particular applications. Operational agencies (e.g., local

government, states, EPA), must consider the requirements for developing and maintaining a workforce trained to use data effectively. A manager must take these considerations into account when determining whether or not to incorporate remote sensing in his/her program.

Applications for the Bay and its Tributaries

The way we view Chesapeake Bay and its watershed has changed significantly since the early 1980s. We have progressed from simply enumerating factors that have culminated in the degradation of water quality and loss of biota, to a focus on setting quantitative criteria to gauge how the ecosystem is responding to management actions. CBP has relied for 19+ years on sampling a set of fixed main stem and tributary stations in an aggressive monitoring program. While this effort is exemplary for estuarine and coastal waters of the U.S., major shortcomings in resolution and coverage have become increasingly evident. We now need to consider how to augment the monitoring program to fill holes in its design and to address scales that are better matched to habitat-level characteristics of the Bay. New technologies are not a substitute for traditional measurements, but with recent advances, we are now poised to integrate remote sensing into monitoring conducted by some of successful programs in the Bay.

From a management perspective, current technologies that generate data at a relatively high spatial resolution, including continuous underway sampling and aircraft remote sensing, lack fine temporal resolution and occur no more frequently than ship-based monitoring cruises. Other approaches, such as sensors mounted on buoys, give "point" data with high temporal resolution, but have limited spatial coverage. Sampling at fixed stations misses a significant part of the Bay's habitat. To date, programs that provide both high spatial and temporal resolution in these undersampled areas are relatively few and have stemmed largely from research projects. One of the major challenges facing scientists and managers is how to merge data and information derived from sampling on these different spatial and temporal scales, taking advantage of the strengths offered by different approaches, to develop the appropriate quantitative understanding of the ecosystem that is necessary to track changes over time.

Chesapeake Bay and its tributaries have been characterized as "impaired" in terms of nutrient and sediment levels, based on provisions of the Clean Water Act (Figure 2). "De-listing" the Bay from its impaired status depends on measurements of sufficient resolution that permit us to quantify improvements of water quality. With CBP's evolving management perspective of what comprises a "restored" Chesapeake Bay and new thinking about how to gauge progress toward this goal, there are growing opportunities to incorporate new technologies with *in-situ* and remotely sensed measurements into the monitoring program. As CBP has moved to define specific Bay criteria for ecosystem properties, including *chl-a*, water clarity, and dissolved oxygen (DO), it has become essential to capture the inherent variability of the ecosystem, — particularly to resolve which changes are the result of management actions from those resulting from largely climate-driven seasonal and interannual variability. If we are able to use contextual data from long-term data sets to improve our capabilities for sampling at higher spatial and temporal resolution, we will be better able to detect and quantify variability that has profound ecosystem ramifications.

Sampling Significant Habitat

Monitoring the main stem of the Bay provides very little data for the extensive shallow regions (1-2 m) that represent important habitat for living resources. To date, water quality in the shallows has been estimated by interpolation from a sparse sampling grid, but significant error accompanies this

procedure. A graphical representation of Bay habitats (Figure 3) illustrates that some of these areas have been significantly undersampled. Submerged aquatic vegetation (SAV), for example, inhabits shallow regions of the Bay and has been critical in management attempts to link water quality to a key component of the biota. But the current emphasis on open water monitoring misses much of the preferred SAV shallow water habitat. This example highlights the mismatch of routine monitoring with the scales of variability for prospective criteria, such as *chl-a* and water clarity, and calls for the use of remote sensing or continuous underway sampling to improve spatial and temporal resolution in under-sampled areas. It is also critical to take measurements that track ecosystem responses to reductions in nutrient loading (N and P) such as *chl-a*, water clarity, and DO. An important question for managers to pose, therefore, is "Can we build a remote sensing component that complements our shipboard measurements to obtain data for the shallows?"

Examples from the Severn River

The utility of new remote sensing technologies for management was demonstrated by data for the Severn River near Annapolis, Maryland presented by Rob Magnien, formerly of Maryland DNR. The Severn is one of many Bay tributaries that is significantly undersampled by routine monitoring, with samples taken from a single station in mid-river on a monthly basis. An examination of two of the water quality criteria, *chl-a* and DO, using an underway instrument and data logging system (Dataflow), revealed spatial and temporal variability not captured by station sampling alone (Figure 4). Transects conducted on two dates in May 2001 show a strong *chl-a* signal with "bloom" concentrations >60 mg m^{-3} over much of the river. An abrupt decline of *chl-a* was detected on a cruise just 10 days later, reflecting the "crash" of the bloom and a return of typical *chl-a* concentrations of 1 to 10 mg m^{-3}. The lesson from this example is that sampling at a single fixed monitoring station, if timed fortuitously, might allow the detection of a bloom, but would not give information on its spatial extent or longevity. A DO depression that accompanied the decline of *chl-a* as the bloom ended would also go undetected with routine sampling.

Undersampling occurs in other habitats as well, including open waters above the pycnocline, deep waters, and the deep channel. Any monitoring program needs to consider the seasonality of key properties, particularly in setting criteria. DO is one example of a strongly seasonal property of the Bay that has direct effects on the Bay's biota (Figure 5), and one that would benefit from expanded sampling.

Main Stem Bay Issues

The current monitoring program for the main stem Bay requires several ships and about three days to occupy ~49 stations. Although ships visit these stations at different times of day and on different days, the accumulated data are then used to reconstruct a month. In the case of *chl-a* and DO, variability within- and between-days can be quite high and cannot be resolved without adding specialized sampling to the core program. A narrow reliance on a traditional water quality program that is not equipped to quantify this variability can lead to significant failings of interpretation, illustrated by continuous measurements of DO (Figure 6).

Watershed Applications

The ability to track changes in land use and land cover is essential in managing watersheds and remote sensing can play an important role over relatively small spatial scales. Modeling and forecasting floods,

for example, requires sophisticated digital elevation models (DEMs) at higher resolution than the current 30-m products that are readily available from the U.S. Geological Survey (USGS).

Todd Schroeder of the Canaan Valley Institute (CVI), a nonprofit, non-advocacy organization located in Thomas, West Virginia, presented examples of some watershed applications. CVI conducted a project on a 900-acre watershed, Fishing Creek in Smithfield, West Virginia (Figure 7), a site that has experienced serious flooding for several years. The existing DEMs were not sufficient to develop forecasts. CVI created an alternative 10-m product from hypsography, and also used LIDAR altimetry data to augment available DEMs and improve predictions of flood impacts. Schroeder indicated that local watershed models also benefit from improved land cover data. He showed an example of such data for part of Fishing Creek acquired with a multispectral digital camera system that helped improve Landsat classification for this watershed by revealing wooded meadows in previously logged areas (Figure 8). Data such as these have also been used in conjunction with DEMs from LIDAR to support advanced modeling of stream flow.

An important facet of the CVI effort is outreach, consisting of several "circuit riders" who organize local watershed groups and formalize efforts in community planning for small towns throughout the region, promoting the use of remote sensing to aid economic and environmental sustainability.

Conclusions

For remote sensing data to be useful in Chesapeake Bay, highly resolved data from buoys, towed bodies, aircraft, and satellites must be integrated with traditional data. One approach is to collect data at high frequency and superimpose them on the long-term record of observations. Fiscal reality will likely prevent CBP from developing its own remote sensing program or equipping the entire Bay with buoys. But remotely sensed or *in-situ* data made available to CBP could be used to improve the understanding of processes in particular areas of the Bay. A number of important management needs have been identified that call for new technologies, and first steps have been taken in test scenarios.
The decline of water quality in Chesapeake Bay, an "impaired" water body that is nutrient- and sediment-enriched and characterized by excess *chl-a*, reduced water clarity, and DO-depletion, has forced the community to re-define the meaning of a "restored" ecosystem. In so doing, we have had to include the underlying diagnostics, i.e., specific impairments associated with specific criteria. At present, data from existing monitoring lack spatial and temporal resolution sufficient to undertake these assessments and need to be supplemented by new technologies. Integrating remote sensing into an overall sampling plan that also uses *in-situ* water quality measurements with sensors moored on buoys, towed from boats or ships, or deployed as drifters, can generate data of high spatial and/or temporal resolution for a number of properties. A fuller utilization and integration of existing technologies, currently available mainly to the scientific community, can significantly impact monitoring in Chesapeake Bay. We must gauge whether a particular technological solution is sufficiently mature that it can be deployed in the near-term and provide sustained data over the long-term. Moreover, new technologies must help address areas of the Bay from the main stem to shallow waters, and measurements must be spatially and temporally integrated with other monitoring components to achieve the objectives of resource managers.
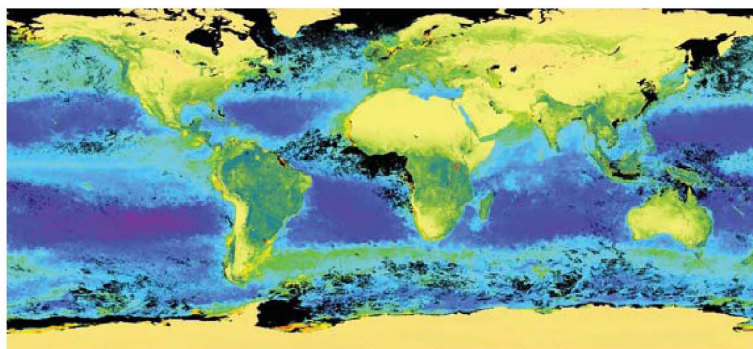
Figure 1. Global chlorophyll (chl-a) in the terrestrial and ocean biosphere from SeaWiFS.

Impaired Waters and Clean-up Plans

Portions of the Chesapeake Bay and its tidal rivers are listed under the Clean Water Act as "impaired waters" largely because of low dissolved oxygen levels and other problems related to nutrient pollution.

This "listing" requires the development of a clean-up plan for the Bay by 2010.

Chesapeake Bay and Tidal Tributary
Nutrient and/or Sediment Impaired Waterbodies
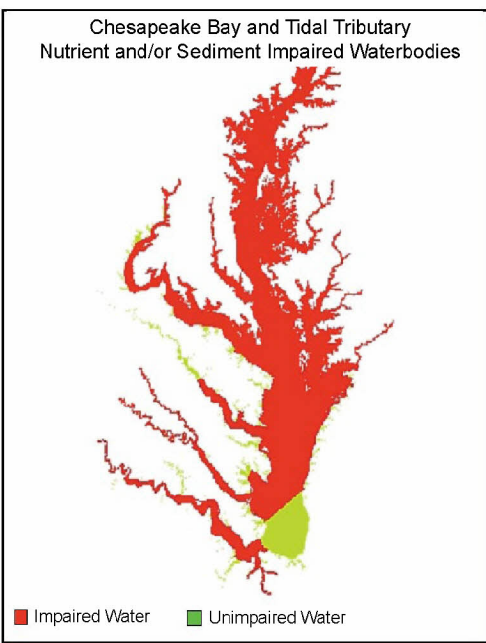
■ Impaired Water   ■ Unimpaired Water

Figure 2. Management stimulus to measure water quality parameters that track nutrient over-enrichment and excess sediment, illustrated as regions of the Bay listed as "impaired" under provisions of the Clean Water Act.

**Refined Designated Uses for
Chesapeake Bay and Tidal Tributary Waters**

A. Cross Section of Chesapeake Bay or Tidal Tributary

Shallow Water
Open Water
Deep Water
Deep Channel

B. Oblique View of the "Chesapeake Bay" and its Tidal Tributaries

Migratory Finfish
Spawning and
Nursery Habitat

Open Water
Habitat

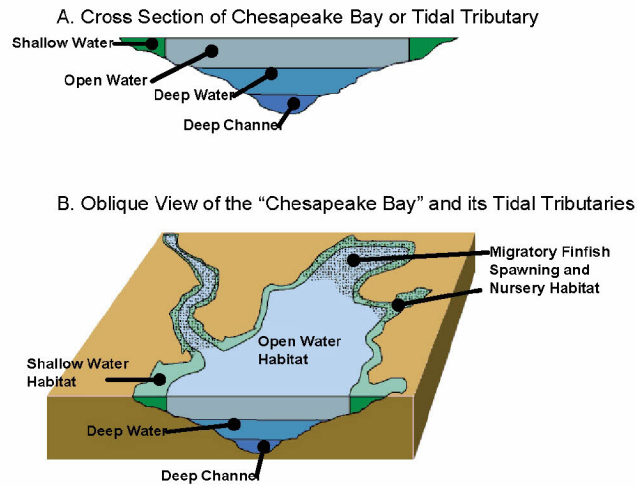Shallow Water
Habitat

Deep Water

Deep Channel

Figure 3. Categories of Bay habitat include shallow water, open water, deep water, and the deep channel. Seasonal water quality criteria for chl–a, water clarity, and DO are being developed for these categories.

05/21/01   05/31/01

Chl (ug/L)
0 - 10
10 - 20
20 - 30
30 - 40
40 - 50
50 - 60
60 - 100
100 - 265

DO (mg/l)
12.5 - 15
10 - 12.5
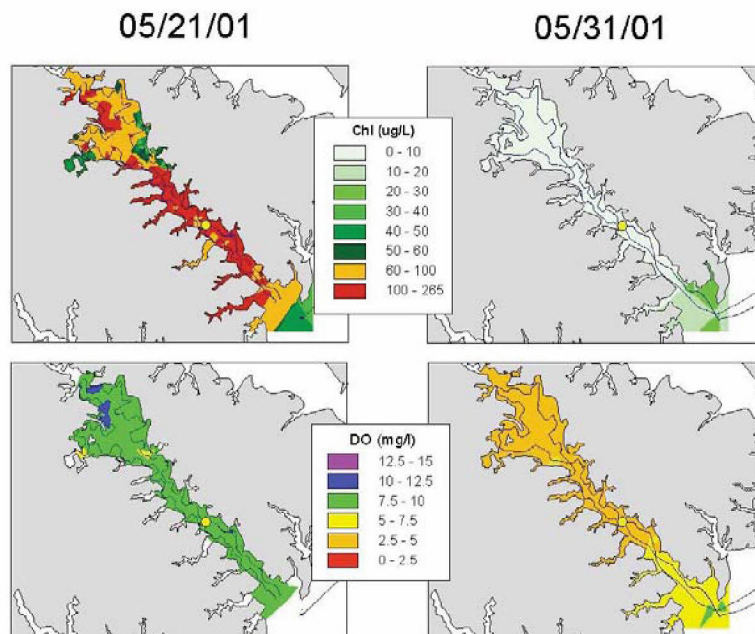7.5 - 10
5 - 7.5
2.5 - 5
0 - 2.5

Figure 4. Examples of chl–a and DO data from continuous underway sampling of the Severn River using the Dataflow system on cruises spaced 10 days apart. The single fixed monitoring station is shown as a yellow dot on each panel.
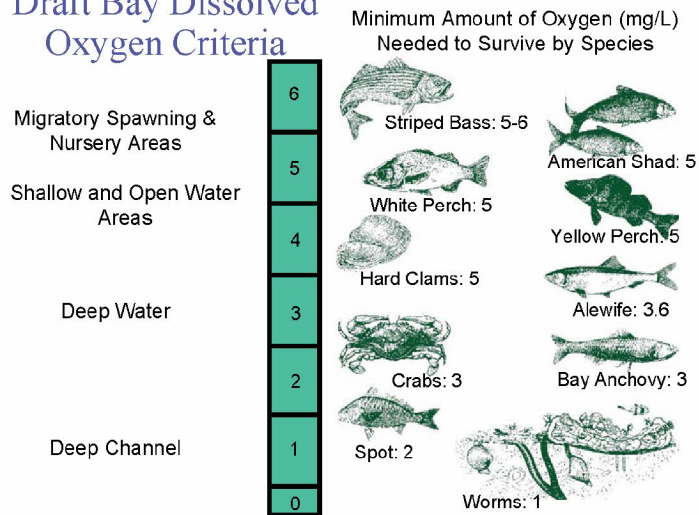
Draft Bay Dissolved Oxygen Criteria

Minimum Amount of Oxygen (mg/L) Needed to Survive by Species

Migratory Spawning & Nursery Areas

Shallow and Open Water Areas

Deep Water

Deep Channel

6
5
4
3
2
1
0

Striped Bass: 5-6

American Shad: 5

White Perch: 5

Yellow Perch: 5

Hard Clams: 5

Alewife: 3.6

Crabs: 3

Bay Anchovy: 3

Spot: 2

Worms: 1

Figure 5. Proposed DO criteria for Bay habitats and the requirements of important macrofauna.

Short term/High frequency

...then superimpose the short term pattern onto the longer term record.
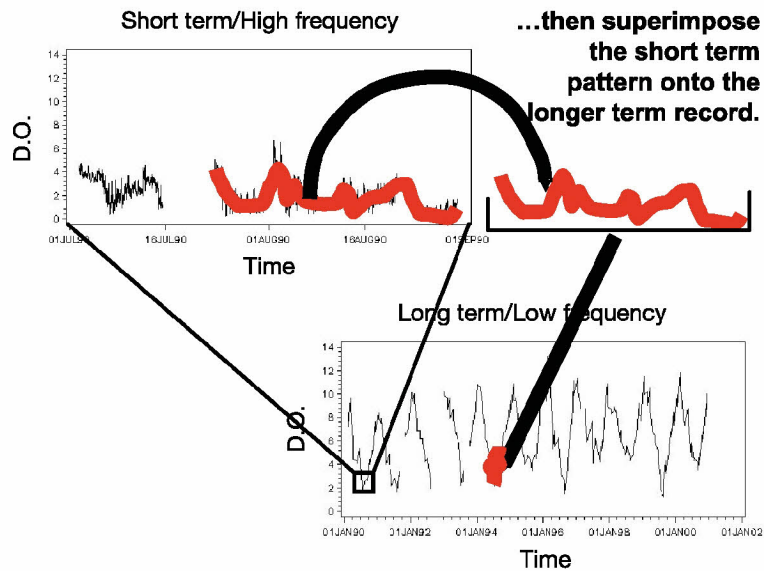
Long term/Low frequency

Figure 6. High frequency measurements of DO superimposed on the diel cycle, showing that instantaneous measurements such as those made at monitoring stations may not capture the temporal variability of this important water quality property.

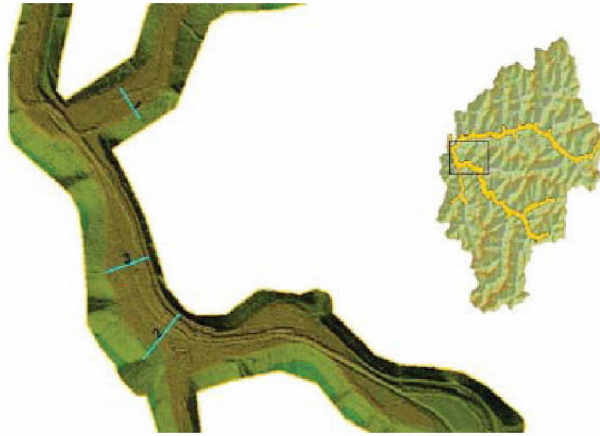*Estuarine and Watershed Monitoring Using Remote Sensing Technology 17*

Figure 7. Local watershed in Smith Valley, West Virginia high resolution DEM product that enables flood modeling and mapping. The yellow lines indicate areas of LIDAR coverage that supported elevation mapping of features not resolved in coarser products.
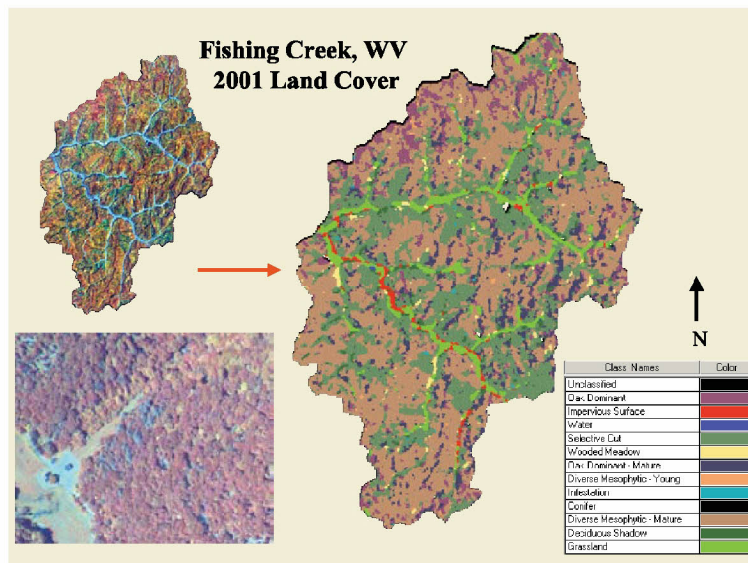

Figure 8. Land-cover classification for Fishing Creek, West Virginia using Landsat data aided by multispectral imagery that revealed wooded meadows in previously logged areas.

Panel Summaries

We convened three panels of scientists and managers to make presentations on existing and projected *in-situ* and remote sensing technologies with applications to Chesapeake Bay. Topics included:

Panel 1 – The Potential Use of *In-situ* Water Quality Measurements with Moored and Towed Instruments

> William C. Boicourt – Horn Point Laboratory, University of Maryland Center for Environmental Science (HPL–UMCES) – Discussion Leader

> Charles Gallegos – Smithsonian Environmental Research Center, Smithsonian Institution (SERC-SI)

> Mary Jane Perry – Darling Marine Center, University of Maine (DMC-U. Maine)

> Richard Batiuk – Chesapeake Bay Program, Environmental Protection Agency (CBP-EPA)

Panel 2 – Airborne/Satellite Measurements of Water Quality

> Lawrence W. Harding, Jr. – Horn Point Laboratory and Maryland Sea Grant, University of Maryland Center for Environmental Science (HPL/MDSG-UMCES) – Discussion Leader

> Blanche W. Meeson – Goddard Space Flight Center, National Aeronautics and Space Administration (GSFC-NASA)

> Janet W. Campbell – Ocean Process Analysis Laboratory, University of New Hampshire (OPAL-UNH)

> Robert E. Magnien – Department of Natural Resources, State of Maryland (DNR-MD)

Panel 3 – Remote Sensing of Land Use/Land Cover in the Watershed

> Stephen D. Prince, Department of Geography, University of Maryland, College Park (Geography-UMCP) – Discussion Leader

> James T. Morris – Department of Biology, University of South Carolina (Biology-USC)
> Thomas R. Fisher – Horn Point Laboratory, University of Maryland Center for Environmental Science (HPL-UMCES)

> Todd Schroeder – Canaan Valley Institute, West Virginia (CVI-WV)

The following sections summarize the proceedings of the panels and assess the applicability of specific *in-situ* and remote sensing technologies to Bay issues.

Panel One: The Potential Use of *In-situ* Water Quality Measurements

Panel One focused on *in-situ* water quality measurements using a variety of sensors that are currently available. Bill Boicourt of HPL-UMCES opened with two observations: (1) monitoring highly dynamic estuaries such as Chesapeake Bay by sampling fixed stations at a relatively low frequency is inadequate to quantify variability of the ecosystem; (2) separating long-term trends in Chesapeake Bay from short-term variability is a pressing need that would benefit from the use of new sensors and techniques.

Moored Instrumentation (CBOS)

Scientists at the University of Maryland Center for Environmental Science (UMCES) launched the Chesapeake Bay Observing System (CBOS) in the late 1980s. CBOS was the first real-time monitoring system in an estuary using instrumented moorings. The goals of CBOS are to augment research on short-term processes and to develop data spanning many years to address long-term ecosystem changes. CBOS consists of several strategically placed buoys with a variety of sensors that report data regularly to ground stations (Figure 9). The system was originally envisioned as a series of six to eight moored platforms along the axis of the Bay, with a plan to expand the array in the next 3-5 years as coastal observing systems in the U.S. continue to develop.

   Strong inputs of fresh water and salt combined with topographical features create regional circulation and biological patterns that can be monitored by a series of platforms along the Bay's 200-mile axis. The intent of the CBOS program is to maintain these platforms as permanent monitoring stations, providing continuous information throughout the year. To complement this permanent array, deployed rover buoys provide increased resolution in areas of special interest, such as the Patuxent River. The first permanent monitoring stations were placed in the northern and middle reaches of the Bay and an additional one was added in 1998, south of the Bay Bridge.

   For over a decade, existing CBOS buoys have provided data on meteorological (air temperature, relative humidity, wind speed and direction), and hydrographic parameters (salinity, temperature, dissolved oxygen, and current speed and direction) in real-time (Figure 10). The buoys have also served as locations to test instruments, including sensors to measure DO, *chl-a*, nutrients (nitrate), and turbidity. Optical sensors have also been deployed to measure incoming solar irradiance and ocean color. There is a plan to add additional buoys in partnership with other institutions on the Bay.
CBOS data were initially transmitted to shore stations using UHF and VHF radios, but the need for higher bandwidths led to the use of spread-spectrum radios for the two newest CBOS buoys. Once data are received at shore stations, they are transmitted via the Internet to a central server at HPL/UMCES in Cambridge, Maryland for processing and visualization, and then delivered to the public on the CBOS web site (http://www.cbos.org). A real-time database engine called AutoMate handles the entire procedure, from acquisition through visualization, including archival and presentation of downloadable data via the web site.

Towed Instrumentation

Towed-body technology is currently used in the Bay to obtain near-synoptic measurements over much wider spatial scales to complement CBOS. SCANFISH™ is a commercial instrument package mounted on a towed body that has been used by the NSF-sponsored Land-Margin Ecosystem

Research (LMER) program on Chesapeake Bay, focused on Trophic Interactions in Estuarine Systems (TIES). It is a "flying wing" towed at 3-5 knots behind a ship and that undergoes programmed depth oscillations to obtain both surface and vertical data (Figure 11A). The instrument is equipped with sensors to measure conductivity, temperature, pressure (depth), DO, *chl-a* fluorescence, and an optical plankton counter (OPC) to measure zooplankton abundance. SCANFISH™ followed a set of tracks repeatedly on seasonal cruises for six years, 1985-2000 (Figure 11B), generating data of high spatial resolution such as those shown for salinity (Figure 11C).

The use of SCANFISH™ in the main stem Bay has provided important insights into biological processes on spatial scales previously unattainable. It would be useful to expand this approach to the shallow reaches of the Bay, particularly in the context of water quality and restoration ecology — monitoring optical properties using continuous surveys near SAV beds, for example. Light availability to the substrate has been implicated in recent declines of SAV in the Bay. Several constituents, suspended particulate matter (SPM), chromophoric (colored) dissolved organic matter (CDOM), *chl-a*, and other plant pigments, all contribute to light attenuation in the water column, controlling the availability of light to SAV. Some of these components are "conservative," that is, they vary as a function of salinity and are traceable to freshwater flow into the Bay. In contrast, phytoplankton biomass, expressed as *chl-a*, is highly non-conservative and has increased historically with increased nutrient loading. SPM and CDOM also vary greatly in space and time; wind mixing, for example, can disrupt bottom sediment in shallow regions inhabited by SAV, restricting light availability and impeding SAV growth. Measuring these constituents in potential SAV habitat is essential to characterize the suitability of water quality in SAV habitat.

Some optical properties are amenable to remote sensing, and several aircraft and satellite instruments are effective for recovering data on *chl-a*, SPM, and CDOM. There are limitations to the accuracy of remote sensing retrievals of optical properties in shallow fringes of the Bay inhabited by SAV: (1) the pixel resolution afforded by satellite instruments is usually ~1 km, and data for shallow waters may contain a mix of optical signals from land and water that complicate the resolution of SAV beds; (2) the relatively small size and curving nature of SAV habitat accentuate the effects of adjacent land in satellite imagery and make it difficult to establish suitable flight tracks for aircraft surveys; (3) bottom reflectance in shallow waters corrupts remotely-sensed data, and correction is impractical in highly variable substrates.

Continuous, underway measurements of optical properties represent a viable, tested approach to collect data in shallow habitats otherwise poorly sampled, including small tributaries, rivers, and shoals. Underway mapping from small boats allows collection of data near the shore at a spatial resolution from 1 to 100 m, closer to the dimensions of SAV beds. This approach is very time-consuming, however, and is best coupled to other, more synoptic approaches to provide a larger spatial context. Chuck Gallegos at the Smithsonian Environmental Research Center has made extensive surveys of optical properties in the Bay (Figure 12). His group measures "inherent" optical properties, such as absorption and backscattering coefficients. Inherent optical properties have distinct advantages as they are largely determined by concentrations of *chl-a*, SPM, and CDOM.

Inherent optical properties are: (1) additive so that the optical properties of the water column, e.g., absorbances, are determined by the summed absorbances of the several constituents; (2) linearly related to concentrations; (3) ingredients of radiative transfer models used to calculate optical properties needed to develop algorithms for remote sensing. Gallegos uses an ac-9 (WET Labs of Philomath, Oregon), an instrument that measures spectral absorbance and transmittance at nine wavebands. Data from underway measurements with the ac-9 have been used to recover information on *chl-a*, SPM, and

CDOM by determining "scaling coefficients" at particular wavebands to quantify absorption by these constituents, leading to a normalized absorption spectrum for each. This approach relies on: (1) the relatively strong absorption of *chl-a* in the red region of the spectrum (676 nm); (2) the similarity of SPM and CDOM absorption spectra; (3) the difference of scattering for these components.

Autonomous Platforms

Another technology with considerable promise for improving sampling resolution is autonomous vertical profiling, using a variety of sensors shown conceptually in Figure 13. These packages run the gamut from instruments deployed at fixed locations with moving components to those mounted on vehicles that drift or move by internal power. One of the main goals of autonomous monitoring is to minimize time-space "aliasing" of measurements, particularly in tidal systems. Moorings that support profiling operate over specified depth apertures and at high vertical resolution. This approach contrasts with CBOS, which deploys instruments at fixed depths, and also with continuous underway measurements that affix instruments to towed bodies or pump water through shipboard instrument packages. The advantage of profiling moorings is complete coverage of the water column that can resolve fine structure that can be missed by instruments spaced vertically on a cable. The disadvantage of any mooring is that measurements are limited to fixed locations, giving spatial coverage defined by the array that one can affordably deploy.

Mary Jane Perry of University of Maine described a set of observations made in Puget Sound, Washington that prompted the development of measurements from a profiling mooring for this region. A strong phytoplankton bloom with *chl-a* of 20 mg m^{-3} occurred inside the Straits of Juan de Fuca, with *chl-a* outside the straits only ~2 mg m^{-3}. Shipboard observations over a 24-h period captured this bloom at a single station as the water mass moved. A routine monitoring program on a fixed sampling schedule, however, would have missed this ten-fold variability of *chl-a*, giving a misleading view of the phytoplankton distribution. Observations such as these led to the use of profiling moorings by the University of Washington (UW) with support from the EPA/NASA Coastal Intensive Site Network (CISNet). The UW instrument was developed to sample vertically for temperature, salinity, and density, generating a record of observations spanning months (Figures 14A-C). This approach has obvious applications in Chesapeake Bay where spatial and temporal variability is strongly expressed.

Vertical profiling moorings face several limitations. The need to secure a constant supply of power can be restrictive, but in Chesapeake Bay the proximity of shore power makes this approach viable. Cables can be run over hundreds of kilometers without a serious loss of power, making most of the Bay accessible to this technology. Shore power has the added advantage that sophisticated instruments can be operated for long periods at high sampling rates. Alternative approaches using instruments with low to modest power requirements are also being developed. Another major impediment to the use of profiling moorings is vandalism. Percy Donaghey at University of Rhode Island has avoided this problem by mounting a vertical profiler on the bottom and reeling instruments up during sampling, limiting the susceptibility to damage at the surface. Biofouling is the most significant obstacle to deploying instruments in estuarine and coastal waters — an issue that pertains both to profiling moorings and to instruments mounted at fixed depths from buoys.

Another approach to obtain vertical data is to use instrumented gliders that undergo lengthy excursions and sample continuously (Figures 15A-C). A glider is an autonomous underwater vehicle (AUV) requiring little power to cover a large area. To date, AUVs and gliders have been deployed primarily to measure water quality, including *chl-a* fluorescence, DO, nutrients, and specific optical prop-

erties, such as those discussed previously. Seaglider is an example of an AUV (Figure 15A), a 1.8 m long, ~50 kg vehicle equipped with a variety of sensors. The instrument has an oil bladder that is used to change buoyancy by repositioning the battery pack along its axis, allowing it to move up and down in the water column, as well as horizontally. It requires very little power and the AUV operates essentially as a glider. Seaglider operated as long as one month in Puget Sound, where it traversed a narrow channel to give repeat coverage. Another experiment with Seaglider was conducted during August 2000 in Monterey Bay, California. Seaglider was released near Moss Landing and allowed to drift for several days, making measurements of *chl-a* fluorescence as it transited offshore along the Monterey submarine canyon (Figure 15B). Gridded and contoured data plotted as a function of along-track distance for a five-day period revealed a subsurface *chl-a* maximum reaching up to 30 mg m^{-3} at depths of 5 to 20 m (Figure 15C).

An effort is underway to miniaturize sensors for AUV deployment, such as a compact fluorometer called the "hockey puck" that measures *chl-a* fluorescence and particle scattering. Other sensors for use on AUVs include "off-the-shelf" DO sensors from SeaBird and spectrophotometric sensors for chemical analyses, including nutrients, such as those developed at the Monterey Bay Aquarium Research Institute (MBARI). Nitrate profiles have been determined by measuring absorption in the ultraviolet (UV) region of the spectrum, although this instrument is presently too large to deploy on drifters and requires a more traditional AUV.

Figure 9. Current and projected placement of instrumented CBOS buoys in mid- to upper Chesapeake Bay.
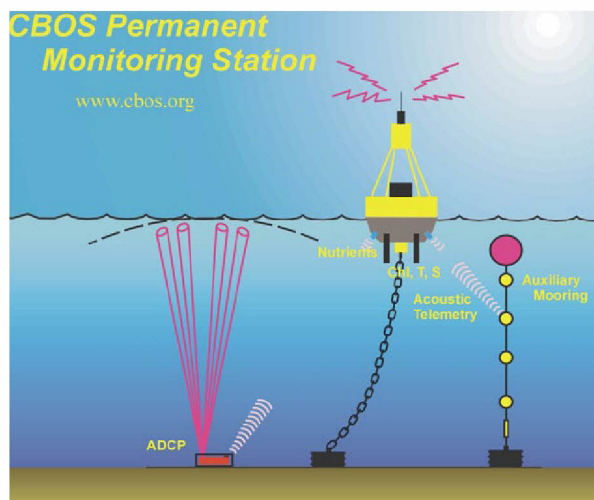

Figure 10. Schematic of CBOS mooring with instruments.

A 1-m SAIL-Loop Sampler

Splitbeam Acoustics

SCANFISH

B
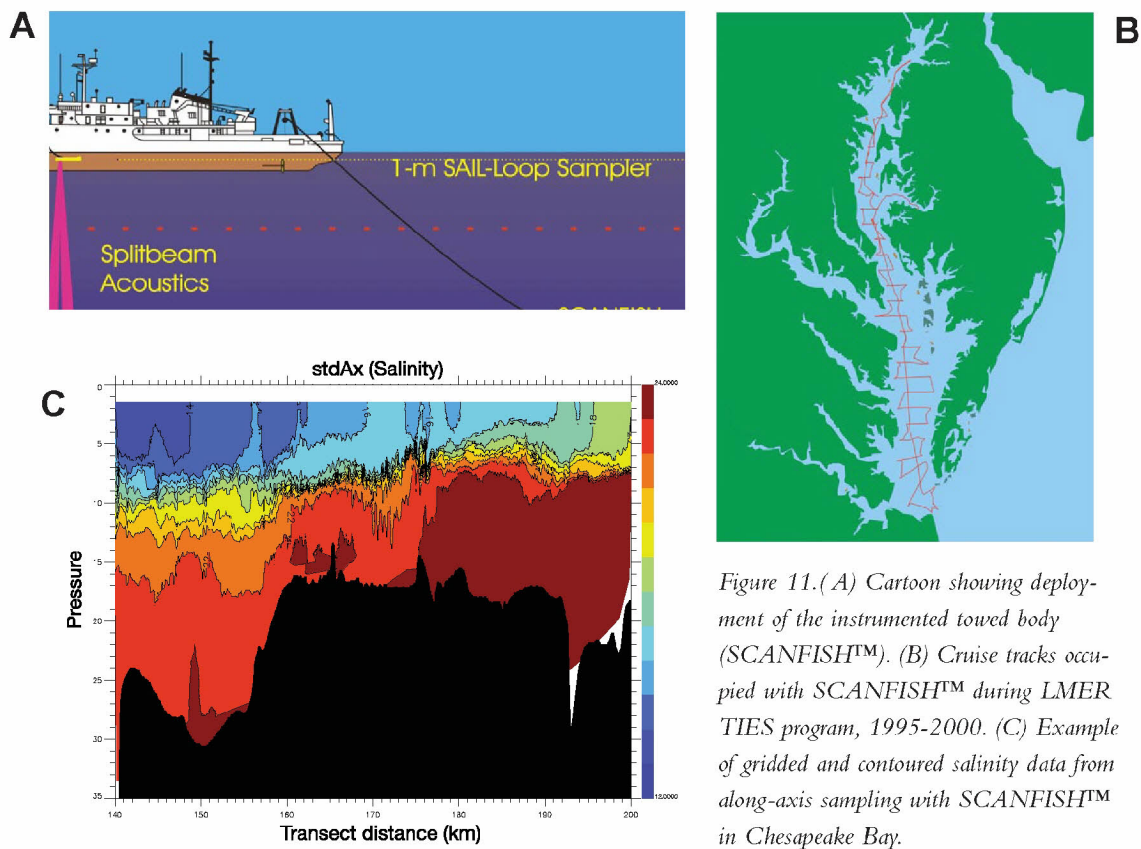
C stdAx (Salinity)

Pressure

Transect distance (km)

Figure 11.(A) Cartoon showing deployment of the instrumented towed body (SCANFISH™). (B) Cruise tracks occupied with SCANFISH™ during LMER TIES program, 1995-2000. (C) Example of gridded and contoured salinity data from along-axis sampling with SCANFISH™ in Chesapeake Bay.
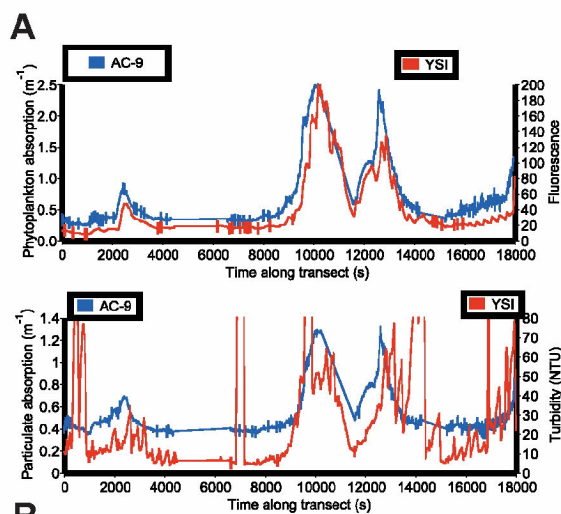

A

AC-9   YSI

Phytoplankton absorption (m^{-1}) / Fluorescence
Time along transect (s)

AC-9   YSI

Particulate absorption (m^{-1}) / Turbidity (NTU)
Time along transect (s)

B

Figure 12. Data from continuous, underway surveys with optical mapping system for: (A) phytoplankton absorption and chl–a fluorescence and (B) particulate absorption and turbidity.
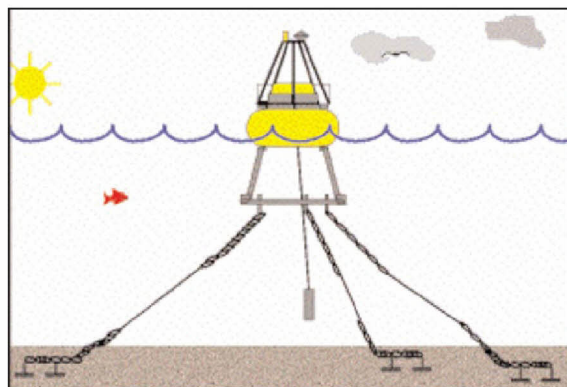
Figure 13. Cartoon showing a mooring equipped for auto-mated vertical sampling.
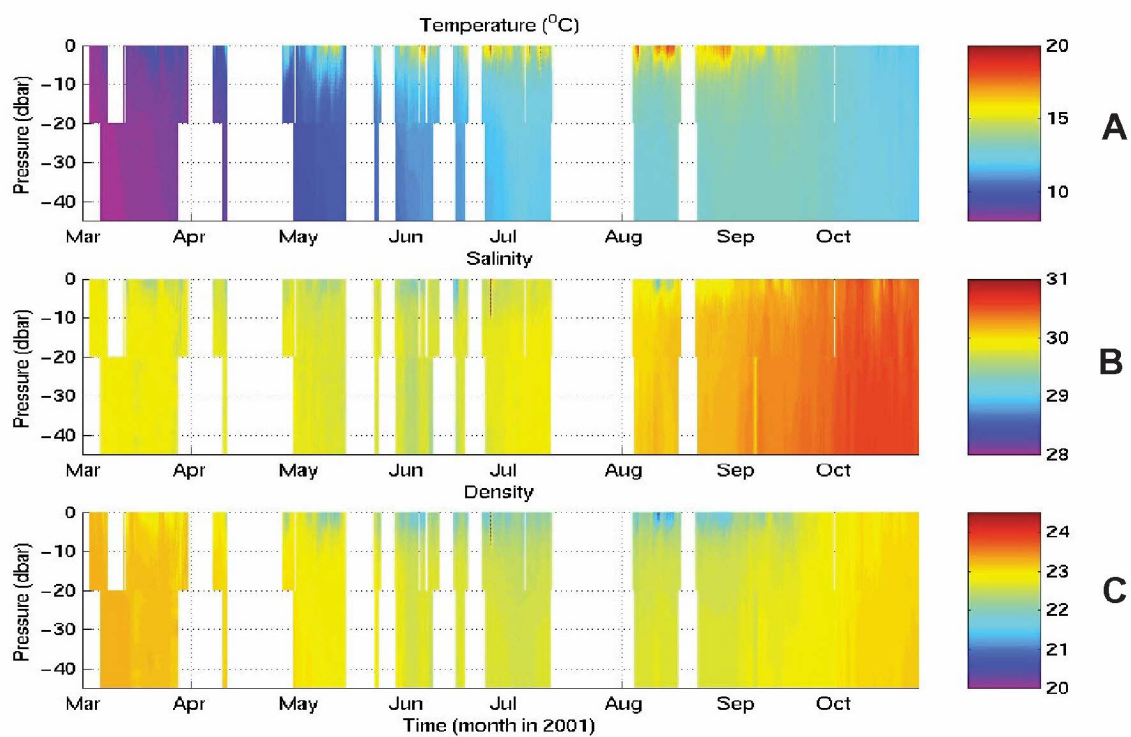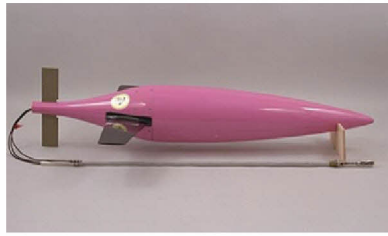

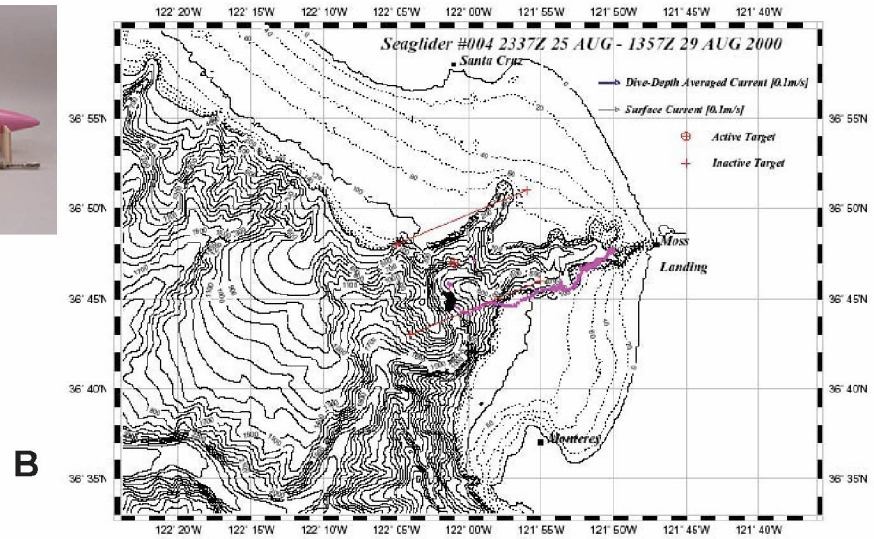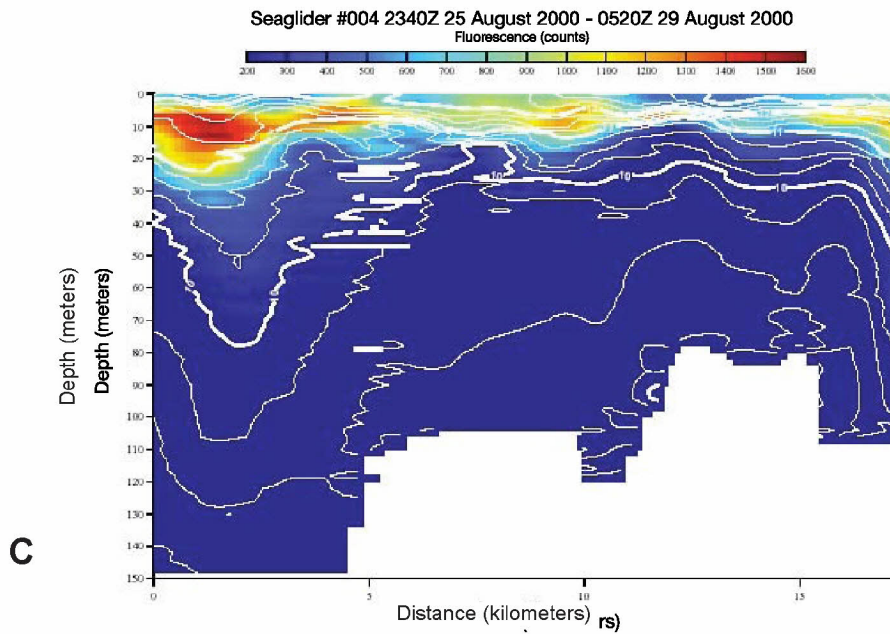Figure 14. Time series of vertical distributions for: (A) temperature, (B) salinity and (C) density from a moored vertical profiler in Puget Sound, Washington.

Figure 15. (A) Autonomous instrument-equipped Seaglider deployed by Erikson and Perry. (B) Track occupied by Seaglider superimposed on bathymetric map of Monterey Bay, California. (C) Horizontal and vertical distribution of chlorophyll from fluorometer mounted on Seaglider.

Panel Two: Airborne/Satellite Measurements of Water Quality

Panel Two addressed a number of applications of airborne and satellite remote sensing of estuarine and coastal waters. These approaches are generating data of interest to the scientific and management communities.

Airborne Remote Sensing (CBRSP)

Larry Harding's group has conducted airborne remote sensing of ocean color on Chesapeake Bay since 1989 as part of the Chesapeake Bay Remote Sensing Program (CBRSP) (Figures 16A-C). The initial motivation of this work was to quantify the high spatial and temporal variability of phytoplankton bio-mass as *chl-a* in the main stem of Chesapeake Bay, driven primarily by variability of freshwater flow from the Susquehanna River. CBRSP uses low-altitude surveys with light aircraft equipped with visible radiometers to measure the spectral quality and quantity of light reflected from the water. These data are used in conjunction with *in-situ* data on optical properties to estimate the Bay-wide distribution of *chl-a* on 20-30 flights per year, totaling over >340 flights to date. The technology used for these measurements has evolved from a three-waveband instrument designed to recover *chl-a* remotely, NASA's Ocean Data Acquisition System (ODAS), through two subsequent generations of instruments manufactured by Satlantic, Inc. of Halifax, Nova Scotia, the SeaWiFS Aircraft Simulator (SAS II, III). The instrument currently being used for Bay flights, SAS III, collects data at 13 wavebands including some specific additions to match capabilities of NASA's satellite instruments, the Moderate Resolution Imaging Spectrometers (MODIS), in the red region of the visible spectrum. CBRSP outputs include interpolated "maps" of *chl-a* and SST from >350 flights. The data are deposited at the NOAA Chesapeake Bay Program Office and eventually will be used to guide criteria attainment, now that specific regional and seasonal targets have been set for *chl-a*. Examples of *chl-a* maps for a sequence of six flights (6 March - 20 June 2000) reveal spatial and temporal variability regularly retrieved using aircraft remote sensing (Figures 17A-C).

The application of remotely-sensed data and information to management needs of Chesapeake Bay centers on the goal of reducing nutrient loading to the estuary, particularly nitrogen (N) as this macronutrient impacts phytoplankton biomass on a Bay-wide scale. Maps that show spatial and temporal variability of *chl-a* in years of contrasting precipitation and freshwater flow can help resolve changes of *chl-a* that are expected to accompany reductions of nutrient loads in the future.

The spring bloom is the most prominent feature of the annual phytoplankton cycle in the Bay. Phytoplankton develop high biomass in spring while incorporating nutrients into particulate organic matter, serving to fuel the Bay's food web and to promote deleterious effects of enrichment, such as low DO. Both scientists and managers recognize that increased nutrient loading to the Bay has acted to "fertilize" the lower estuary, alleviating N limitation and supporting increased phytoplankton biomass. The effect on the ecosystem appears increased *chl-a* in the polyhaline regions, particularly from the 1950s to the 1980s. Since 1989 when CBRSP began, there has been strong interannual variability of *chl-a* in the polyhaline areas coupled to freshwater flow. Low-flow years are characterized by reduced spring biomass, evident in *chl-a* images from aircraft remote sensing, whereas high-flow years typically have high biomass in the mesohaline to polyhaline regions. The complete time-series of *chl-a* data from aircraft remote sensing has been combined with models of primary productivity (PP) developed by Harding's group. From these data, monthly "climatologies" of *chl-a*, euphotic-layer *chl-a*, and PP for 1989-2001 have been developed, supporting predictive models for these ecosystem properties. The

strengths of this approach are the high spatial and temporal resolution attained in the time series, careful calibration of instruments, generation of algorithms and models, and independent validation using data from a variety of sources, among them the CBP monitoring and LMER TIES programs.

Satellite Remote Sensing

Satellite-based remote sensing has many applications in estuarine and coastal waters. Janet Campbell of OPAL-UNH presented a brief history of ocean color remote sensing (Table 1). This approach originated with the launch of the Coastal Zone Color Scanner (CZCS) aboard the Nimbus-7 satellite in 1978. CZCS was operational for eight years with products consisting of surface maps of "pigment" concentrations including both *chl-a* and degradation compounds (phaeopigments) not distinguished from active *chl-a*. CZCS was a proof-of-concept mission that gave extensive coverage of the oceans from scenes combined over relatively long (monthly, annual) time periods to produce a global view of pigment distributions. Following CZCS, there was a 10-year absence of satellite ocean color data until the Ocean Color and Temperature Sensor (OCTS) was launched in 1996. This short-lived mission provided data for less than a year before instrument failure. In August 1997, the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) was launched. SeaWiFS is owned and operated by a commercial company, Orb Image, and NASA has purchased the rights to the data and has provided them to the research and education communities at no cost. SeaWiFS nominally acquires complete global coverage every two days (http://seawifs.gsfc.nasa.gov), although cloud cover lessens this frequency. A combination of three SeaWiFS bands to simulate red, green, and blue light reflected from the ocean is used to create a "true color" image, as shown in an example for coastal waters near Cape Hatteras, North Carolina, illustrating the effects of Hurricane Floyd (September 1999) on turbidity (Figure 18). Bright blue corresponds to a predominance of "blue" water as one might see from a ship on the open ocean, whereas vegetation on land is green. Bright colors (yellow) correspond to high reflectance and indicate suspended matter mixed into the upper ocean as a result of the hurricane's passage.

Sensor	Satellite	Country	Dates	Spatial Resolution	No. of Bands	Comments
CZCS	Nimbus-7	USA	Nov 78 – Jul 86	825 m	5	Proof-of-concept
MOS	IRS P3	Germany/ India	Mar 96 –	523 m	13	Requires ground station
OCTS	ADEOS-1	Japan	Aug 96 – Jun 97	700 m	8	+ 4 thermal IR bands for SST
SeaWiFS	SeaStar	USA	Aug 97 –	1100 m	8	Commercial data, free to researchers
OCI	ROCSAT-1	Taiwan	Dec 98 –	800 m	6	Latitude coverage 35N-35S
OCM	OceanSat-1 (IRS P4)	India	May 99 –	360 m	8	+ Scanning microwave - SST
MODIS	Terra	USA	Dec 99 –	1000 m	9	+ 27 other bands for land, atmos, SST
OSMI	KOMPSAT-1	S. Korea	Dec 99 –	850 m	6	Selectable bands

Table 1. Characteristics of ocean color sensors (past and present). Arrows indicate ready availability of data. Note there are now two MODIS instruments with the second on Aqua.

Despite the availability of rich sources of data, Campbell observed that managers seldom access them and often view the learning curve to develop expertise as a barrier. Consequently, most remain unfamiliar with products that can be obtained that don't require technical expertise in image processing or interpretation. Campbell specifically noted the availability of numerous products from the NASA Distributed Active Archive Center (http://daac.gsfc.nasa.gov) with potential applications for coastal managers. The DAAC represents an entry point for access to data and information from a growing set of ocean color sensors with increasing capabilities in coastal waters.

Satellite remote sensing offers the advantage of regular, synoptic coverage by instruments that generally take data for years once they are launched, distinguishing this approach from airborne remote sensing whose advantage is spatial resolution. In the past few years, NASA has supported extensive work using SeaWiFS in Chesapeake Bay, including optical sampling to support the analysis of regional SeaWiFS data (Figures 19A, B). SeaWiFS *chl-a* images have ~1 km resolution (same resolution as gridded and contoured aircraft products presented by Harding). For the main stem of Chesapeake Bay, this resolution is clearly appropriate to describe the major features of the annual phytoplankton cycle in the Bay, including the spring diatom bloom and summer outbreaks of dinoflagellates. Recent advances have allowed us to generate time series of *chl-a* for the period 1998-2003, based on the use of semi-analytical models tuned with local optical data that give accurate *chl-a* retrievals for the Bay.

New ocean color instruments are currently in orbit with greater capabilities than SeaWiFS. These include the Moderate Resolution Imaging Spectrometer (MODIS) launched on the Terra satellite platform in December 1999, and a second MODIS launched on the Aqua platform in April 2002 (http://modis. gsfc.nasa.gov). Both Terra and Aqua are part of NASA's Earth Observing System (EOS) that consists of large platforms carrying multiple sensors to measure a variety of environmental parameters. MODIS represents a state-of-the-art ocean sensor for earth imaging, as shown in SST and *chl-a* data for the Arabian Sea (Figures 20A, B). Terra and Aqua MODIS generate SST and *chl-a* products at 1 km for the global ocean, comparable to the spatial resolutions of the NOAA Advanced Very High Resolution Radiometer (AVHRR) for SST and SeaWiFS for *chl-a*. The 36 spectral bands of MODIS include several with higher spatial resolution, with five bands at 500 m and two bands at 250 meters. MODIS generates a large number of ocean products, including four measurements of SST, and five estimates of PP for the terrestrial and ocean biosphere. (Since the workshop, the product suite of MODIS has been edited to include fewer standard products.) In addition to ocean products used to retrieve *chl-a* and PP, MODIS provides a *chl-a* fluorescence product that relies on solar-stimulated fluorescence in the red region of the visible spectrum. The ratio of *chl-a* fluorescence to *chl-a* concentration is a measure of "fluorescence efficiency," believed to give information on the photosynthetic potential of phytoplankton. A sequence of sensors, from SeaWiFS to MODIS, and eventually to new missions such as the National Polar-orbiting Operational Environmental Satellite System (NPOESS), will generate *chl-a* for two decades, providing coverage required for resolving long-term trends from variability.

The higher-resolution bands of MODIS can be combined to produce composite images that have potential application to Chesapeake Bay. Qualitative information on SPM contained in such images can be used to track water movements and define the spatial extent of riverine influence. Campbell presented recent work to develop an index of fluvial influence (IFI) based on this approach. Elevated SPM in water from the Mississippi produces an increase of water-leaving radiance at 550 nm (L_w 550) that can be used to show movement of the freshwater plume (Figure 21). Campbell suggested the IFI has direct applicability for tracking water movements in the Bay and in adjacent waters of the middle Atlantic bight.

Satellite sensors provide data on a number of optical properties that can be used to estimate important ecosystem attributes. For example, time series of *chl-a*, K, SST, and PP can already be

obtained from several current satellite instruments, and other instruments are scheduled for launch in the coming decade. Calibration and validation are essential to recover accurate information from satellite sensors, and to this end, the combination of remote sensing with *in-situ* optical measurements is critical. The need for comparable data from different sensors led to the NASA project, the Sensor Inter-comparison and Merger for Biological and Interdisciplinary Oceanic Studies (SIMBIOS). SIMBIOS has supported a range of data collection and analysis activities, including optical sampling in diverse waters of the world's oceans, to calibrate and validate algorithms, and to compare properties retrieved from instruments with different capabilities.

NASA is funding a new program directed at applications to promote "partnering" with prospective users of data and information developed by the scientific community. There are uses for data and information from satellites other than the original scientific purposes, especially as components of education and outreach efforts. Campbell described a project in Maine entitled "Gaia Crossroads" that uses satellite imagery in K–12 classrooms to stimulate interest in the environment and promote the use of earth system imagery to engage students in science curricula.
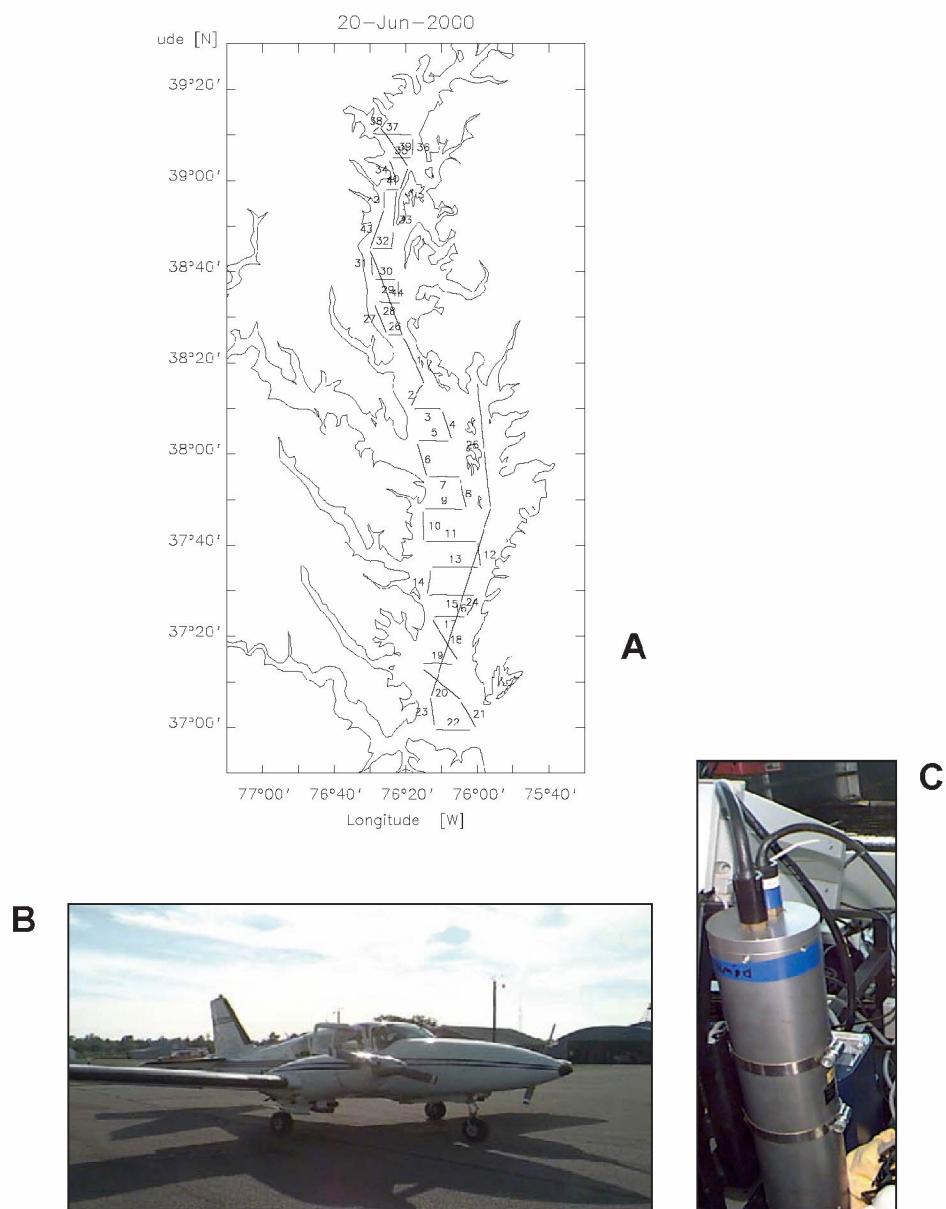
Figure 16. (A) Flight tracks for aircraft remote sensing of ocean color in Chesapeake Bay. (B) Piper Aztec currently used for main stem Bay flights. (C) SAS III radiance sensor mounted in the aircraft.
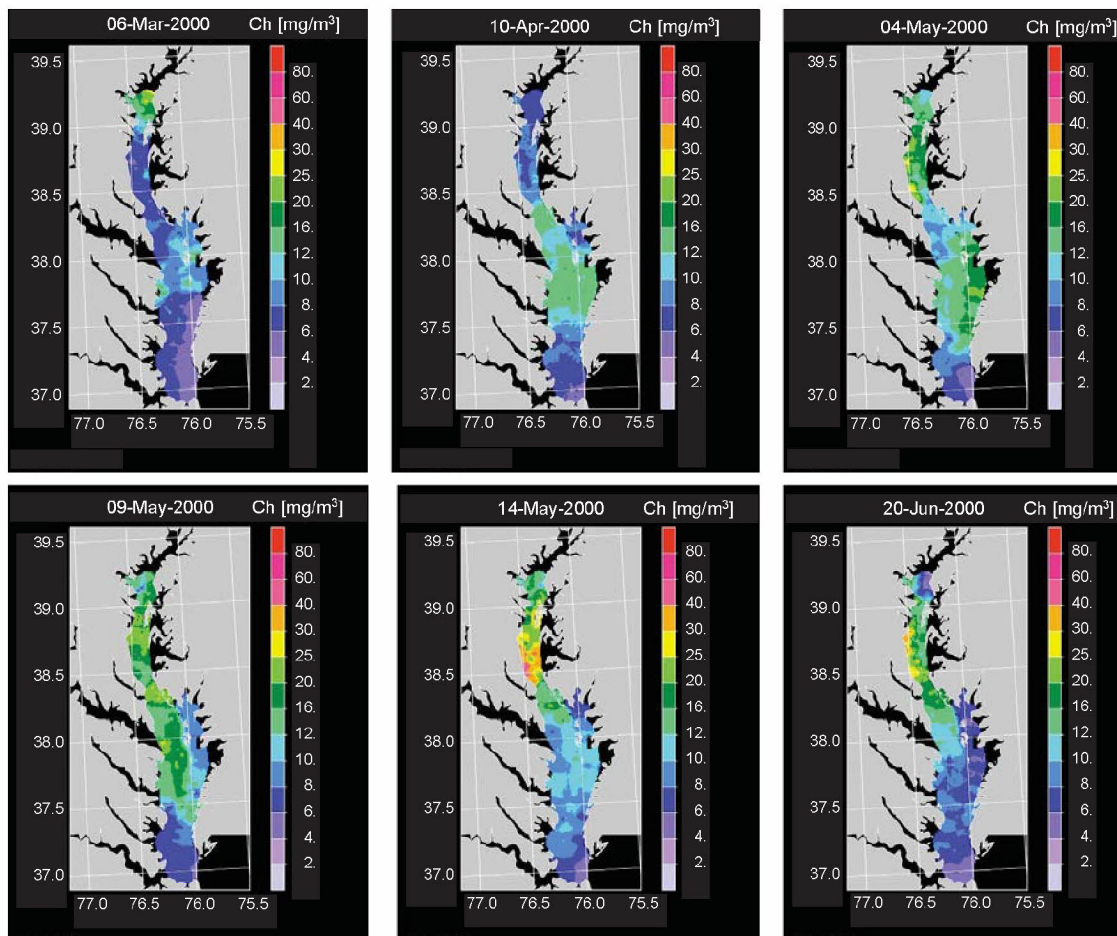
Figure 17. Chl–a concentrations in the main stem of Chesapeake Bay from aircraft remote sensing of ocean color using the SeaWiFS Aircraft Simulator (SAS III) for six flights in spring 2000.

Figure 18. True color image from the Sea-viewing Wide Field-of-View Sensor (SeaWiFS) of the Middle Atlantic, showing the effects of Hurricane Floyd adjacent to Albemarle-Pamlico Sound, North Carolina.

SeaWiFS chl-a (mg m⁻³) on April 12, 1998

A
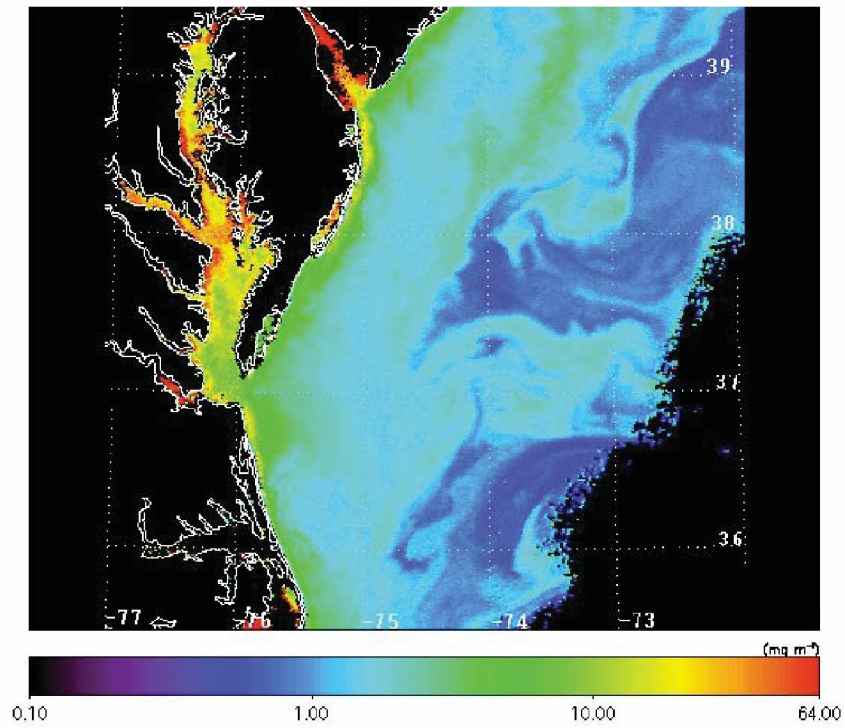
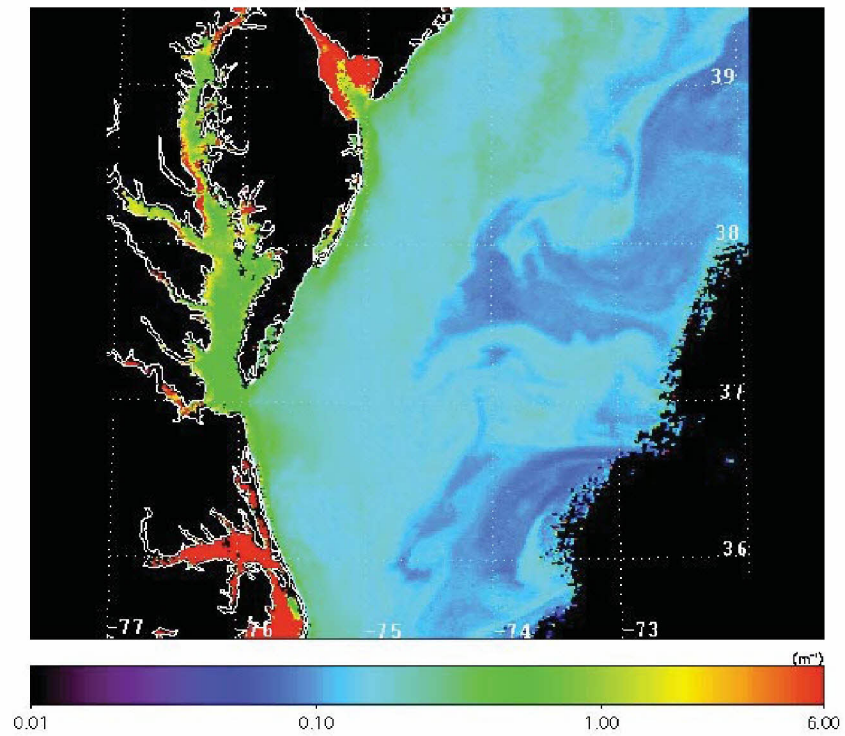*SeaWiFS K490 (m⁻¹) on April 12, 1998*

B

Figure 19. (A) SeaWiFS chl-a and (B) K490 images for the middle Atlantic Bight including Chesapeake Bay.
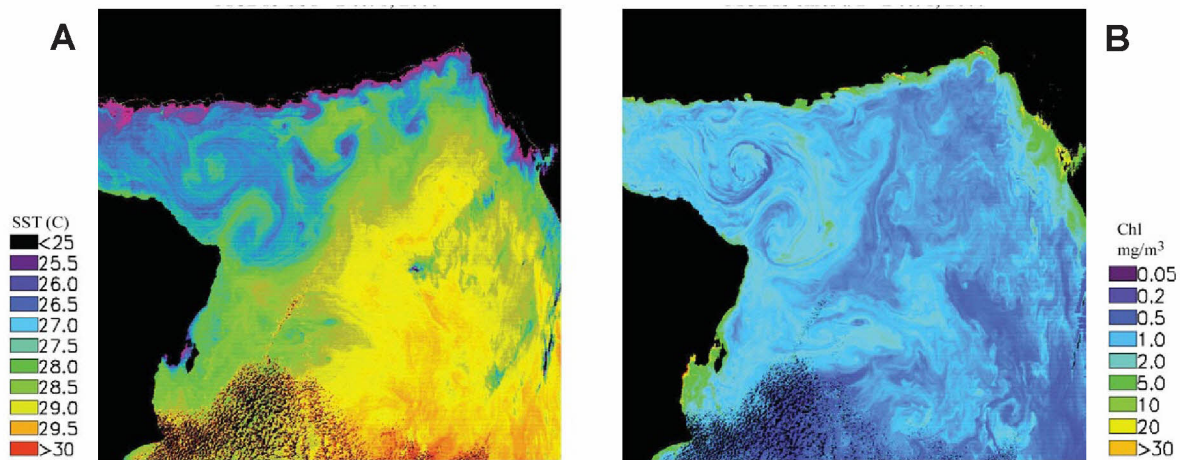
Figure 20. MODIS data for the Arabian Sea, 1 December 2000 (A) SST and (B) chl-a.

Figure 21. Index of fluvial influence (IFI) for the Mississippi R. plume (Salisbury et al., 2000).

Panel Three: Remote Sensing of Land Use/Land Cover in the Watershed

Panel Three focused on land use and land cover in the Bay watershed in a departure from discussions of *in-situ* and aircraft/satellite remote sensing. Steve Prince of the University of Maryland, College Park noted that our emphasis on *in-situ* and remote sensing measurements of water quality in receiving waters of the Bay leads naturally to a focus on the land, where many of the problems originate. He stressed the need for comprehensive, consistent maps that cover the Bay watershed. Historic mapping has played an essential role in monitoring and analysis, providing a spatial context for land management and planning on local and regional scales. Many of the maps currently in use are, in fact, derived from remote sensing. A fundamental change from the "old days" of remote sensing manifests as an appreciation of data and information derived from new technology, including recognition that variables we retrieve are far more quantitative than mere pictures. These comments echoed a theme introduced earlier that the jump in quality of data and information is traceable to extensive calibration and validation that are integral elements of contemporary remote sensing.

Habitat protection and restoration are specific issues that benefit from improved characterizations of stream corridors, riparian buffers, and wetlands. The commercial satellite instrument, IKONOS, from Space Imaging, Inc., is an example of new technology that provides imagery of increased spatial resolution (1 to 4 m) useful to delineate forested riparian buffers, in Montgomery County, Maryland (Figure 22). A combination of radar and optical approaches has also been applied to resolve ambiguities of boundaries in mapping wetlands. Prince showed an example of Synthetic Aperture Radar (SAR) and Landsat Thematic Mapper (TM) imagery that have been used for this purpose (Figure 23).

Quantifying impervious surfaces in urban and suburban areas of the watershed using remote sensing data has been a major emphasis of RESAC. Prince showed an example of GIS data layers gridded at a spatial scale of 3 m^2 and combined into blocks of 30 m^2 (Figure 24). Each of the 100 units comprising the blocks was categorized as impervious or not, generating a "binary" product. These products were then binned to give the percentage of impervious cover on a spatial scale of 30 m^2. This approach gives detailed information to classify thematic data and is amenable to machine-learning techniques, providing a map of impervious surfaces in the Baltimore and Washington, D.C. area, rivaling the content and quality of photographic sources (Figure 25). Prince also presented examples of remote sensing data and information used to characterize the land surface, including DEMs that are essential to quantify topography underlying stream maps and to estimate runoff. Airborne LIDAR is currently used for topographic mapping, as discussed in a subsequent presentation by Morris that addresses sea-level rise and marsh elevation.

Remote sensing has increasing value for evaluating the effects of climate change in coastal wetlands. The C2K Agreement mandates "no net loss" of existing wetlands, a goal that contradicts one of reducing sediment loads to the Bay, since survival of wetlands in the face of sea-level rise depends on a sufficient sediment supply. To evaluate effects of climate change on Bay wetlands, it is necessary to separate long-term trends from short-term variability, as depicted for sea level near Charleston, South Carolina and Boston, Massachusetts (Figure 26). These elevation data from surveys over 80 years show that sea-level rise does not occur as a simple linear trend indicated by the regression slope of 0.3 cm y^{-1}, but is punctuated by increases and decreases that can be on the order of tens of centimeters. Resolving the long-term, low-frequency signal from short-term variability is a significant challenge.

Sea-level rise is expected to impact marshes in several ways, including changes in: (1) the

absolute and relative elevations of coastal wetlands; (2) total wetland area; (3) the location of wetlands as migration of existing wetlands and colonization of terrestrial habitats occur; (4) wetland community boundaries; (5) total and area-specific productivity; (6) landscape scale patterns within wetlands. Many of these changes can be detected remotely. Marsh surface elevations will also increase, as shown in the example for North Inlet (Figure 27). A key question that new technology could help address is, "Will increases of this magnitude keep pace with sea-level rise?" Based on this dataset, the slope is >0.5 cm yr^{-1} for a period of four years, indicating that at least over a relatively short period of time, marshes kept up with the long-term trend of sea level. On the other hand, short-term trends exemplified by the Charleston and Boston sea-level data exceeded increases of marsh elevation. The record for annual primary production from South Carolina marshes spanning almost two decades shows interannual variability superimposed on the long-term trend (Figure 28). The upward trend of primary production could be due to the fact these marshes are not keeping up with sea-level rise. These marshes are perched at a very high elevation within the intertidal zone, and occur at super-optimal elevations with respect to plant productivity. As sea level rises relative to the elevation of the marshes, productivity improves until the marsh surface reaches an optimal elevation, and then a continued rise of sea level crosses a threshold and productivity declines.

Landsat imagery of North Inlet shows the effectiveness of the Enhanced Thematic Mapper (ETM) for capturing differences in plant communities (Figure 29). Forest, *Spartina* marsh (green), and brackish marsh (red) are readily distinguishable in this example. The spatial resolution with the ETM is 30 m, and this instrument is well suited to quantify the total area of different coastal wetland habitats. Plant pigment signatures provide information on environmental conditions in wetlands. The rationale for making such measurements is that an underlying environmental condition, such as a change in nutrient status or nutrient loading, evokes changes in the distributions of pigments in leaves that can be resolved by examining hyperspectral data. Figure 30 shows a typical reflectance spectrum for a leaf of *Spartina alterniflora*. There is a region in the visible part of the spectrum where reflected light depends primarily on the assortment of pigments, especially chlorophylls, but also on the secondary pigments. There is also a region in the near infrared (NIR) where cell structure and anatomy are most important, and a region in the short IR where water absorption is very important. Pigment spectra for *S. alterniflora* in unfertilized vs. P-fertilized plants are significantly different in the NIR (Figure 30). These reflectance differences should be detectable using remote sensing, as should environmentally relevant variations in the other spectral regions.

Various kinds of multispectral remote sensing data are available to assess the status and trends of wetlands in the Bay, particularly the boundaries and patterns of these environments. LIDAR can be used to track changes of elevation and perhaps to measure canopy heights and biomass. Hyperspectral data may provide information on the level of stress in plant communities. Thermal imaging and fluorescence are also promising technologies that may give insights to stress in plants.

Remote sensing imagery enables visualization and interpretation of land cover and land use. Tom Fisher of HPL-UMCES drew a clear distinction between the two concepts. Land cover is "what you see in an image" when you look at a land surface, e.g., wetlands, grasslands, or forest. Land use is how that land cover is being used. For example, a classification of forest cover could have a number of distinct uses, including forest itself (i.e., state or federal forest), undisturbed primary forest, multi-use parkland, a Christmas tree farm, abandoned farmland. All these uses interact very differently with the environment, and are important in determining how a particular cover mediates N and P export and CO$_2$ sequestration. A commercial forest may export more N and P to streams than would parkland or undisturbed forest because of fertilization and disturbance. An undisturbed primary forest may not

remove as much atmospheric CO_2 as a young, rapidly growing forest since net primary production approaches zero in older forests when primary production and respiration are balanced. Many models used to estimate export from a terrestrial basin into an aquatic system require data on land use rather than land cover.

Analysis of land cover change is essential to gain a historical perspective. Land cover data can be reconstructed using satellite imagery originating with the first Landsat satellite with the Multispectral Scanner (MSS) launched in 1972. Images are available for the period 1972 to 1978. The Thematic Mapper (TM) is a more recent Landsat instrument, available from 1982 to the present and the Enhanced Thematic Mapper Plus (ETM+) has recently become available on Landsat 7.

These instruments have different spatial resolutions — 80 m for MSS, 30 m for TM, and 15 m for ETM+. In the 1930s, aerial photographs taken at decadal intervals mapped the continental U.S., and these photographs provide high-resolution imagery on the order of 2 m (depending on the time period, flight altitude, etc.). These aerial photographs are available from USDA for the period 1937 to the present. Other historical maps produced for various purposes are available at irregular intervals and are often very useful to reconstruct land cover.

There are a number of important considerations for reconstructing land cover from different data sources, particularly spatial and spectral resolution of the underlying data. Spatial resolution differs among instruments and approaches and the extent of coverage has changed in the past several decades. The availability of multiple sources of imagery is key, as sensors of differing capabilities have overlapping temporal coverage and a range of spatial and spectral resolutions. Higher resolution aerial photographs or maps can be used to improve upon lower spatial resolution Landsat TM imagery. For example, an aerial, color infrared photograph taken in 1988 improved upon the Landsat TM to obtain land use and land cover data for Easton, Maryland (Figure 31). TM imagery indicated "agriculture" in the center of the town of Easton (yellow within the red area) that was actually parkland with the spectral signature of grass. Photographic data were used to make this correction.

A major effort of Fisher's research group has been to combine historical and contemporary data from a variety of sources to analyze land cover changes in the Choptank River basin since colonial settlement. Historical maps from 1850 and 1900 have been used to estimate 19th century land cover in the basin, and aerial photographs from 1937, along with a series of Landsat MSS and TM images for 1972 to 1996 have been used to characterize agriculture, forest, and urban areas. This analysis shows that the Choptank River basin has been predominantly agricultural for >100 years (Figure 32). The area has remained relatively stable in agriculture, although there has been a slight decline since ~1900 due to steady urbanization over that time period.

Information on hydrology can also be derived from remote sensing imagery and used to estimate the effects of land-use changes on nutrient input. Land cover has a large impact on hydrology and is an important input to most water quality models. For this application, the differences between land cover and land use may be insignificant since forest hydrology is stable compared to urban hydrology. Forested areas have good infiltration, a large base-flow component, small storm flow, whereas forests absorb water, retain it, release it slowly, and have low erosion rates. Urban areas, in contrast, have poor infiltration, a small base-flow component, and large storm flows. This produces flash flows with high erosion rates. Land cover and land use also have profound impacts on hydrology and stream chemistry. Forests affect stream chemistry because they retain nutrients, and the export of N or P from forested areas is low, both in loss rates and concentrations. Streams in urban and agricultural areas have much higher nutrient concentrations, and greater export as higher concentrations are coupled with flash runoff.

Two examples of products derived from land use and land cover clearly illustrate the utility of such data. In the first example, groundwater nitrate concentrations, expressed as a function of land use, showed a strong influence of forests in retaining nitrate (NO_3) compared to fertilized agricultural fields and septic systems that export large amounts of NO_3^-. In the second example, N export from the river basin to the Choptank River was estimated from historical changes of land cover and a common hydrologic model, the Generalized Watershed Loading Functions (GWLF), to show a tenfold increase since ~1900 due to the application of fertilizer through agricultural fields.
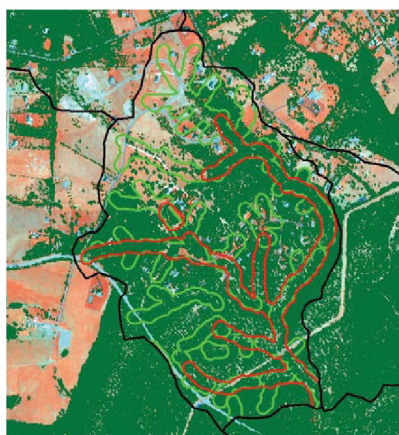
IKONOS Statistics for Forested Riparian Buffers

Riverwood Area, Mont. Co
30m Buffer

Current Hydro Layer
85% forested

5' Topo DEM Hydro Layer
65% forested

Figure 22. Riparian buffers based on imagery from the commercial satellite IKONOS (Space Imaging, Inc.) for Montgomery County, Maryland.

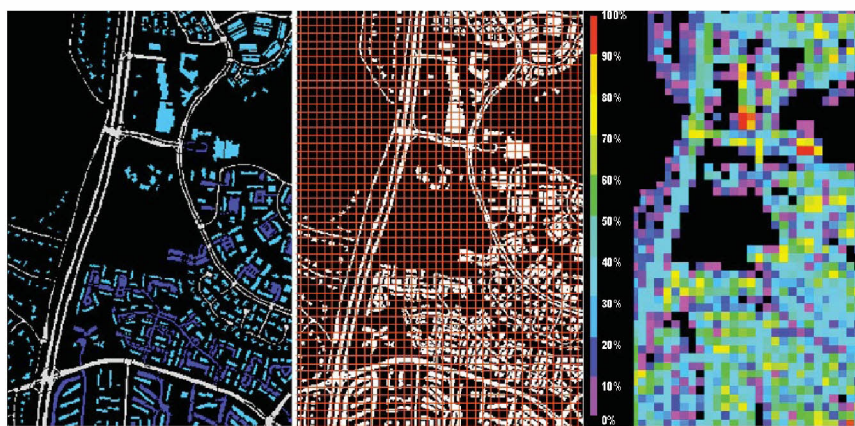## Wetlands as Viewed with Synthetic Aperture Radar and Optical Data

Multitemporal SAR

Landsat TM (June)

Figure 23. Synthetic Aperture Radar (SAR) and Landsat Thematic Mapper (TM) views of wetlands.

Vector Extraction ——————→ 3m to 30m Grid ——————→ %Impervious Cover

GIS Processing Steps– Training Data

Figure 24. GIS processing steps for deriving percent impervious cover.

Air Photos(1990)　　　　　　　　**Landsat Derived**

Sub-Watersheds
- 0 - 5% Impervious
- 5 - 10% Impervious
- 10 - 20% Impervious
- 20 - 30% Impervious
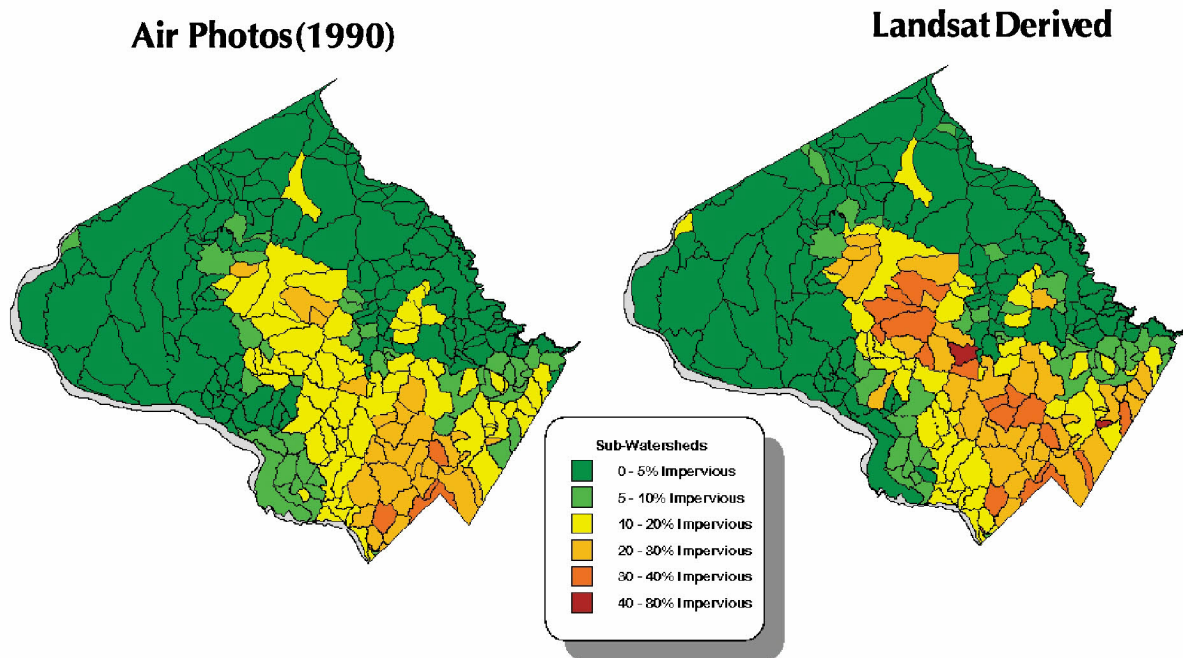- 30 - 40% Impervious
- 40 - 80% Impervious

Figure 25. Small area impervious cover identified using aerial photography and Landsat data.
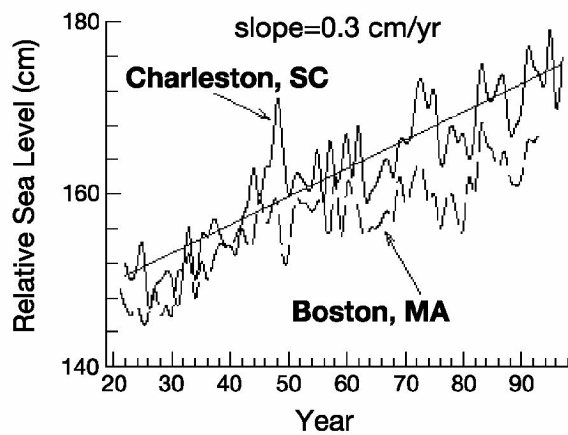

Figure 26. Sea-level and marsh-elevation rise at Charleston, South Carolina and Boston, Massachusetts.
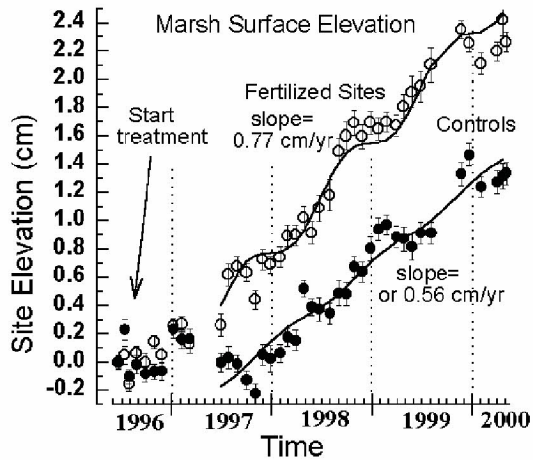
Figure 27. Rise of marsh surface elevation in control and fertilized sites in North Inlet, South Carolina.
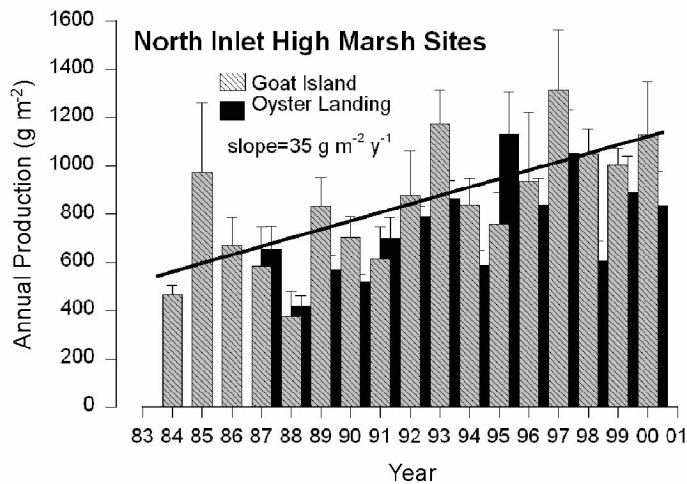
Figure 28. Annual primary production (g m⁻²) at two sites in North Inlet, South Carolina – 1984-2001.

Plant Community Boundaries with Landsat ETM

Forest

Spartina marsh

Brackish marsh

30 m resolution, coverage every 16 d
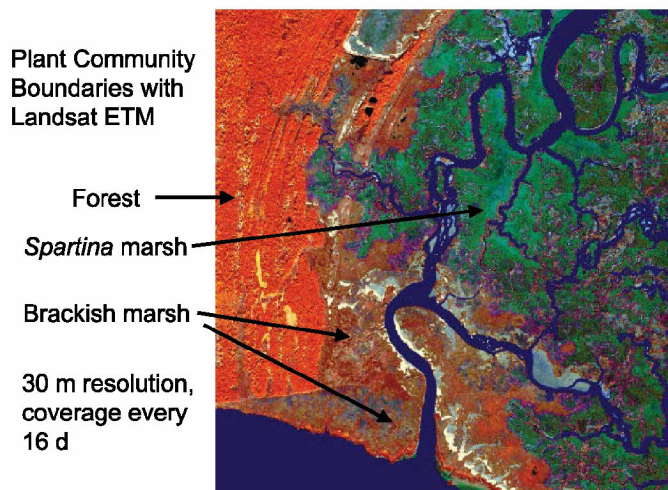
Figure 29. Landsat Enhanced Thematic Mapper (ETM) coverage of North Inlet showing plant community boundaries.
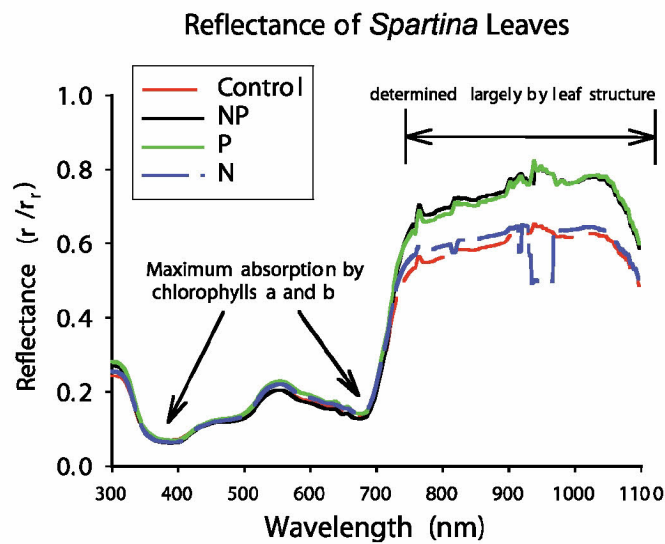
Figure 30. Spectral differences in control and fertilized Spartina alterniflora *leaves associated with structural changes in the leaves.*
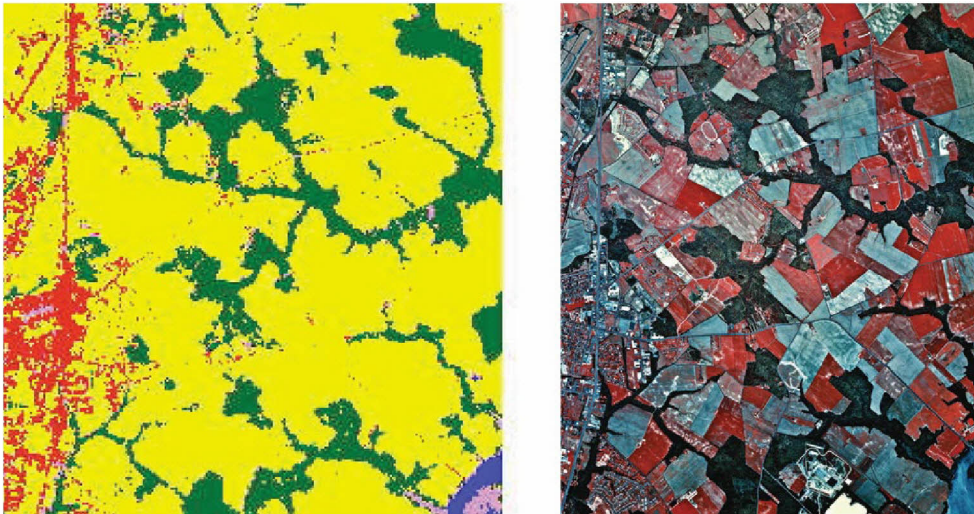
Figure 31. Landsat TM image of the Easton, Maryland area and an aerial, color infrared photograph of the same area.
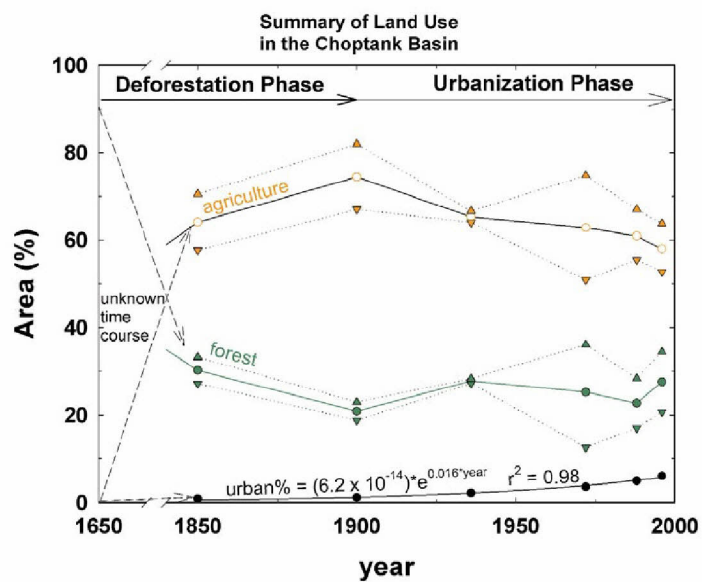
Figure 32. Reconstruction of historical land cover based on several data sources including old maps, photographs, and remotely-sensed imagery. Dotted lines are estimates of confidence intervals.

Working Groups — Water Quality and Land Use/Land Cover

In the second part of the workshop, attendees were divided into two concurrent working groups, focusing on issues pertaining to water quality and land use/land cover, respectively. These discussions culminated in a plenary session designed to address how remote sensing could be applied to the goals and obligations articulated in the C2K agreement. The group reached a consensus that there are several existing technologies that can be used now, and several others currently under development that have potential applications. Several of the managers attending the workshop were already aware of some remote sensing capabilities that could be directed at their needs. However, there is still no systematic integration of remote sensing with managers' needs and data and information from remote sensing are not used extensively to further management goals. The following sections summarize discussions of the work groups and make recommendations for linking of new technologies to management needs.

Water Quality Working Group

Participants agreed that remote sensing of water quality has direct applicability to broad goals of the C2K Agreement, such as:

- Achieve and maintain the water quality necessary to support the aquatic living resources of the Bay and its tributaries and to protect human health;

- Preserve, protect, and restore those habitats and natural areas that are vital to the survival and diversity of the living resources of the Bay and its rivers;

and to more specific goals, such as:

- Recommit to the existing goal of protecting and restoring 114,000 acres of submerged aquatic vegetation (SAV). By 2002, revise SAV restoration goals and strategies to reflect historic abundance, measured as acreage and density from the 1930s to the present. The revised goals will include specific levels of water clarity that are to be met in 2010. Strategies to achieve these goals will address water clarity, water quality, and bottom disturbance. By 2002, implement a strategy to accelerate protection and restoration of SAV beds in areas of critical importance to the Bay's living resources;

- By 2001, define the water quality conditions necessary to protect aquatic living resources and then assign load reductions for nitrogen and phosphorus to each major tributary;

- Using a process parallel to that established for nutrients to determine the sediment load reductions necessary to achieve the water quality goal;

- By 2002, complete a public process to develop and begin implementation of revised Tributary Strategies to achieve and maintain the assigned loading goals;

- By 2003, the jurisdictions with tidal waters will use their best efforts to adopt new or revised water quality standards consistent with the defined water quality conditions. Once adopted by the jurisdictions, the Environmental Protection Agency will work expeditiously to review the new or revised standards, which will then be used as the basis for removing the Bay and its tidal rivers from the list of impaired waters;

- By 2003, work with the Susquehanna River Basin Commission and others to adopt and begin implementing strategies that prevent the loss of the sediment retention capabilities of the lower Susquehanna River dams.

The water quality working group began its discussions by focusing on potential solutions to existing problems, emphasizing the emerging CBP criteria for *chl-a*, water clarity, and DO. Measures of light attenuation, primarily from the perspective of habitat suitability for SAV, were deemed very important. Managers Batiuk and Magnien praised the utility of simple measures of light attenuation, such as Secchi depth, to estimate K_{par} on a Bay-wide basis. Secchi depth, a measure of the depth to which a white disk can be seen from the service, has been used to define light penetration in the main stem of the Bay and major tributaries for many years by calibrating readings with more sophisticated measurements from submersible irradiance sensors. There is a mismatch, however, between the sites where these measurements have been made and prospective SAV habitat. Several participants noted that shallow areas, representing historical and current SAV habitat, have not been sampled adequately by the set of monitoring stations now used to measure *in-situ* optical properties.

Participants discussed the potential to use remote sensing methods to address this deficiency. Past work using data from Landsat and AVHRR gave estimates of total suspended solids (TSS) from satellite data, but these products were primarily used to track sediment plumes in water bodies with strong land to sea gradients of TSS, such as Delaware Bay. The estimates of K_{par} from these measurements had a stated accuracy of $+$ 0.1 m^{-1}, perhaps sufficient to map optical conditions coarsely for large systems, but it is not clear that data from these sources would be useful for shallow waters. The spatial resolutions of Landsat and AVHRR are probably not suitable to characterize optical properties of SAV habitat, although retrievals of K_{par} from both instruments deserve testing as they might be useful to estimate K_{par} for the main stem of the Bay and large tributaries. K-products are now available from SeaWiFS and MODIS that permit estimates of K_{par}, but the accuracy of these products for specific regions of the Bay still needs to be ascertained.

Continuous underway mapping of optical properties described by Gallegos could directly address this issue and more fully characterize the light environment for SAV. Several advantages accompany the measurements he described. These include collection of optical data near SAV beds, areas that are not generally sampled by monitoring cruises and that for various reasons (bottom reflectance, adjacency to land) are inaccessible to remote sensing. Local processes such as resuspension of bottom sediment, patchy plankton distributions, and inputs of SPM and CDOM from tributaries, affect *in-situ* optical properties on relatively small scales, amenable to measurements using instruments such as the ac-9. Two water quality criteria for the Bay, *chl-a* and water clarity, are retrieved by continuous underway measurements and linked to optical properties quantitatively, enabling a detailed examination of attainment of these criteria in SAV habitat in the context of light availability. This is an important step that has ramifications for the prediction of habitat suitability on an ecosystem scale.

Several speakers (Boicourt, Gallegos, Perry) addressed the usefulness of continuous underway sampling as a way to obtain data of high spatial resolution for a variety of water quality characteristics

in key locations. Deployment of towed or autonomous bodies instrumented with sensors to measure *chl-a* fluorescence and other optical properties (SCANFISH™, Seaglider) could significantly augment spatial coverage from traditional sampling, and in the case of the optical package used by Gallegos, access shallow water. The Severn River example is another such application wherein a small boat equipped to make underway measurements continuously revealed spatial variability not resolved in the monitoring program. The limitation of this approach is temporal coverage. Instruments such as SCAN-FISH™ and Seaglider are more useful as mapping tools and require repeated deployment to generate a time-series. Supplementing data collection of this type with moored instruments would help achieve the goal to obtain data at more frequent intervals at sentinel locations and to address event-scale changes.

The working group also discussed the use of new technologies to quantify SAV in the Bay. The long-term monitoring of SAV abundance presently relies on photogrammetric data acquired annually from an altitude of 12,500′ using light aircraft. Several participants addressed the limitations of this approach, principal among them the lack of synoptic coverage. Flights occur over a period of several months at different stages in the plants' annual grow-out. As a historical record the data are consistent, but the lack of synoptic coverage lessens their usefulness to track changes of SAV distributions that are manifested locally and may not be captured by the existing approach. Other technologies include high-resolution commercial satellite data (IKONOS, Space Imaging, Inc.). IKONOS is a space-borne instrument that provides multispectral data at high spatial resolution. Unfortunately, the data are expensive and the quality is highly variable, depending on the level of processing purchased. For the purpose of characterizing interannual differences of SAV coverage, it is not clear that the existing SAV monitoring program would be improved by obtaining multispectral satellite data. Paired sampling using aerial photography and satellite data, however, should occur to determine advantages realized with new technologies.

Participants explored issues involved with *in-situ* and remote sensing of *chl-a*, one of the most important indicators of water quality in coastal and marine ecosystems and one that is highly responsive to nutrient loading, discussing *in-situ* measurements of *chl-a* from buoys, towed bodies, AUVs, and from instrument arrays on small boats. Several themes emerged: (1) fixed-station monitoring on a monthly to twice-monthly basis is very useful to provide context and addresses seasonal and interannual variability of *chl-a* quite successfully; (2) temporal variability of *chl-a* on scales from days to weeks is not well captured by this approach; (3) spatial variability of *chl-a* on scales from tens of meters to kilometers is not quantified by this approach; (4) high frequency measurements of *chl-a* using fluorometers on buoys can augment the frequency of sampling at individual moorings; (5) underway sampling from boats and ships, or with instrumented towed bodies and AUVs, offer approaches that increase spatial resolution.

Remote sensing approaches to measure *chl-a* were discussed in detail. Ocean color instruments have been flown on light aircraft in the Bay for 15 years, giving high spatial and temporal resolution for *chl-a* and SST. These data have direct applicability to assess compliance with water quality "criteria" as *chl-a*. Satellite data from several sources have also gained utility in the last three years. SeaWiFS data for 1998-present have been validated for the mesohaline and polyhaline regions of the Bay. The improved retrieval of *chl-a* from SeaWiFS has been made possible using semi-analytical models that use local optical data as inputs, rather than radiance-ratio algorithms used in bulk processing. These locally tuned semi-analytical models are now being implemented with the processing of SeaWiFS and MODIS data and coupled to new approaches for atmospheric correction, resulting in accurate retrievals of *chl-a* for a significant part of the main stem Bay.

The advantages of satellite data are frequent, synoptic coverage. For example, there are data from about 14-18 monitoring cruises per year, depending on the year, 20-30 flights per year, and ~100 cloud-free SeaWiFS scenes per year for the Bay. The spatial resolution is also much improved by remote sensing of *chl-a*. Airborne sensors generate products with an along-track resolution of ~5 to 50 m and satellite sensors have pixel sizes ~1 km or finer. Two current instruments, Terra MODIS and Aqua MODIS, offer improvements to SeaWiFS with a number of additional products of direct interest to managers and scientists, including data from multiple passes per day, K and PP products, additional bands in the red region of the spectrum that may extend the useful range of recoveries to high *chl-a* in blooms, and bands at finer spatial resolution that are promising for highly dynamic coastal waters.

Working group participants also discussed novel approaches that may be useful to monitor water quality. Some have been used in Chesapeake Bay and other systems as a part of ongoing research initiatives. These include moored NO_3^- sensors such as those deployed in the Choptank River as part of the CBOS and CISNet programs (Boicourt), the IFI used for tracking the Mississippi River plume in the Gulf of Mexico (Campbell), automated vertical profilers described for Puget Sound (Perry), and the Dataflow system described for the Severn River (Magnien). These approaches extend the products we can generate using *in-situ* and remote sensing approaches.

Water quality criteria for *chl-a*, light attenuation, and DO provided an important context for the working group's discussions. One element of monitoring that has not received sufficient attention is the extent to which fixed-station measurements provide the spatial and temporal resolution needed to determine if a specific tributary or region is in compliance with water quality criteria. Participants discussed the strengths and limitations of spatial "interpolation" of monitoring data to address compliance, i.e., how well does the current station grid serve the need to quantify water quality properties when spatially explicit solutions are "derived" rather than measured. Current attention is being given to interpolation methods applied to several data sources, including fixed-station shipboard sampling, underway sampling, and remote sensing from aircraft and satellite instruments to ascertain if more highly resolved data are useful to address compliance. This is an important use of the data from a management perspective.

Other aspects of sampling the Bay fall more in the "research" arena and have value to managers in explaining processes, but less clear links to their immediate needs. An important example would be SCANFISH™ surveys conducted in the LMER TIES program from 1995 through 2000 (Boicourt and Roman). The results have provided highly resolved data on salinity, temperature, density structure, *chl-a*, zooplankton, and DO for dynamic regions of the Bay. The data Perry presented for Monterey Bay also demonstrate the rapid changes in distributions of key properties that demonstrate fixed-station sampling may be inadequate to characterize an ecosystem. Some small-scale, rapid changes are relevant to both scientists and managers, however, as discussed for examples of ephemeral "events" including harmful algal blooms (HABs) and pulsed nutrient inputs.

Land Use/Land Cover Working Group

Specific goals of the C2K Agreement in the areas of wetlands, forests, land conservation, development, and transportation have potential remote sensing applications. These include:

Wetlands

- By 2010, achieve a net resource gain by restoring 25,000 acres of tidal and non-tidal wetlands. To do this, we commit to achieve and maintain an average restoration rate of 2,500 acres per year basin wide by 2005 and beyond. We will evaluate our success in 2005;

- Provide information and assistance to local governments and community groups for the development and implementation of wetlands preservation plans as a component of a locally-based integrated watershed management plan;

- Establish a goal of implementing the wetlands plan component in 25 percent of the land area of each state's Bay watershed by 2010. The plans would preserve key wetlands while addressing surrounding land use so as to preserve wetland functions;

- Evaluate the potential impact of climate change on the Chesapeake Bay watershed, particularly with respect to its wetlands, and consider potential management options.

Forests

- By 2002, ensure that measures are in place to meet our riparian forest buffer restoration goal of 2,010 miles by 2010;

- By 2003, establish a new goal to expand buffer mileage. Conserve existing forests along all streams and shorelines. Promote the expansion and connection of contiguous forests through conservation easements, greenways, purchase and other land conservation mechanisms.

Land Conservation

- By 2001, complete an assessment of the Bay's resource lands including forests and farms, emphasizing their role in the protection of water quality and critical habitats, as well as cultural and economic viability;

- Permanently preserve from development 20 percent of the land area in the watershed by 2010.

Development, Redevelopment, and Revitalization

- By 2012, reduce the rate of harmful sprawl development of forest and agricultural land in the Chesapeake Bay watershed by 30 percent measured as an average over five years from the baseline of 1992-1997, with measures and progress reported regularly to the Chesapeake Executive Council.

Transportation

- By 2002, the signatory jurisdictions will promote coordination of transportation and land use planning to encourage compact, mixed-use development patterns, revitalization in existing communities and transportation strategies that minimize adverse effects on the Bay and its tributaries.

The discussion of land use and land cover detailed a number of advances in the use of remote sensing data that have clear applicability to these C2K goals. Fortunately, there are tremendous regional capabilities in the academic and government communities (i.e., the RESAC at the University of Maryland). A number of analyses are currently being pursued that include land use and land cover mapping with a variety of airborne and satellite sensors. Both the RESAC and UMCES have developed strong working relationships with state and federal partners.

Specific C2K mandates and goals that pertain to land use and land cover are implicitly associated with remote sensing data and information. A clear consensus developed in the working group to support more effective application of land use and land cover data to track changes in the Bay's watershed. Most analyses to date have used data and information for specific periods of time separated by a decade or more, a temporal resolution that is probably inadequate to track changes. Verification of riparian buffers, agricultural uses, and urban expansion are examples of changes that cannot be detected with occasional analysis of Landsat data alone. A recurrent request we heard expressed was to obtain Landsat ETM+ imagery for the Bay's watershed annually, and to develop the capability at CBP to analyze these data and track changes.

Participants in the working group agreed that another essential role of remote sensing is to follow changes in land use and land cover that have ramifications for water quality. Recurrent analyses of Landsat data should, therefore, be coupled to efforts in total manageable daily loads (TMDL) and in modeling runoff. We reached a consensus that it is essential to test model predictions with observations, yet this has often been done inadequately or not at all, particularly for water quality projections and despite the availability of a strong monitoring program. Model scenarios need to include "what if" approaches wherein impacts of specific actions on nutrient inputs are assessed, i.e., adding buffer strips to particular locations, removing agricultural fields, upgrading wastewater treatment facilities. The endpoints of such efforts should include assessments of the impacts of specific management practices on key properties, such as *chl-a* and SAV, thereby quantifying ecosystem responses to specific actions.

An explicit goal of the C2K Agreement is the permanent preservation from development of 20% of the land area in the watershed. Agriculture, as opposed to sprawl or increased impervious substrate, might be viewed as "preservation," despite the fact that agriculture can have a significant negative impact on the Bay by increasing nutrient runoff. Preservation, in this case, might be viewed as negative, absent improvements to control nutrient runoff from this land use. On the other hand, if the alternative was development or sprawl, it might be viewed as positive step.

The amount of impervious cover in the watershed has a direct bearing on the movement of pollutants into receiving waters of the estuary. Participants agreed that quantifying impervious cover is essential to gauge inputs of nutrients and pollutants from urban and suburban areas to streams, rivers, and the Bay. Remote sensing has proven valuable to identify and quantify impervious cover and is thereby relevant to language of the C2K Agreement on development, redevelopment, and revitalization. We need analytical tools that will allow local governments to conduct watershed-based assessments that aid in making informed decisions about development, transportation, and growth that entail

limits to impervious surfaces. Regular Landsat ETM+ acquisitions are applicable to quantify impervious surfaces and could be augmented with higher resolution imagery from IKONOS to improve the validation and interpretation of the coarser resolution ETM+ imagery. Participants suggested that a good approach for CBP would be to focus on priority urban watersheds identified in the C2K Agreement, such as the Anacostia River, Baltimore Harbor, and Elizabeth River, which are designed to be models for urban river restoration in the basin.

The C2K Agreement stipulates both retention and restoration of wetlands, accentuating the need to use the "best tools" to quantify their extent, composition, and health. Participants discussed several current examples of how airborne and satellite instruments are used to map wetlands, distinguish plant types, and detect plant stress in the flora. The use of multispectral and hyperspectral instruments provide greatly improved resolution in UV, visible, and IR regions of the spectrum, offering the potential to distinguish healthy from unhealthy plants in wetlands. An essential tool to project the long-term stability of wetlands is the accurate determination of elevation using LIDAR. This may be impractical for the entirety of Bay wetlands, but quantifying the elevations of intertidal wetlands relative to mean sea level would be a reasonable beginning to assess marsh stability. High-resolution DEMs can be constructed for this purpose and also have applicability to local and regional issues such as flooding. C2K also commits to promoting the expansion and connection of contiguous forests through conservation easements, greenways, etc. Remote sensing imagery is essential to quantify the distribution of forest and its fragmentation, but in a watershed such as that of Chesapeake Bay, it is essential to differentiate actual forests from similar land covers, i.e., forest strips around housing developments, whose functions may differ significantly in terms of nutrient sequestration.

Recommendation Steps

Here, we restate the specific recommendations emerging from the workshop that we presented at the beginning of the Report, and develop specific steps relevant to each recommendation as bullets.

- **Expand and Better Integrate *In-situ* Technologies.** *In-situ* technologies have been in use by the scientific community for many years and a variety of high-resolution data products are currently available. Expanding the use of a range of methodologies, from continuous underway sampling to deploying new sensors on buoys, will greatly enhance monitoring capabilities, particularly in tributaries and the shallow reaches of the estuary.

  - Expand the use of high resolution, continuous underway sampling *in-situ* to augment long-term, fixed-station monitoring, particularly in areas of the Bay, such as shoals and tributaries, that are not well sampled in the core monitoring program;

  - Integrate high-resolution data from *in-situ* "mapping" with contextual data provided by long-term monitoring to improve the usefulness of both data streams;

  - Add capabilities to *in-situ* sampling with new sensors that can be deployed on buoys, towed bodies, and AUVs, particularly to measure *chl-a*, optical properties, and nutrients;

  - Increase the use of high-resolution data from the research community that has developed CBOS, SCANFISH™, Dataflow, and underway optical mapping;

  - Use *in-situ* and remote sensing data to gauge improvements of water quality associated with mandated nutrient reductions in concert with model projections by validating the models with actual data;

- **Expand the Use of Aircraft and Satellite-based Sensors.** Remote sensing from aircraft and satellite platforms offers great promise to expand synoptic measurements and to examine understudied regions of the Bay. Partnerships with key agencies (NASA and NOAA) and better utilization of multiple data products, many available at no cost, should be pursued.

  - Make better use of airborne remote sensing of *chl-a* and SST for the Bay in the context of criteria attainment and compliance;

  - Deploy airborne sensors for key properties in regions of the Bay that are under-sampled at present, such as the tributaries;

  - Develop partnerships with scientists in academics and government agencies to facilitate the use of satellite data on *chl-a*, K, SST, and PP for the Bay;

  - Increase awareness of the multiple products that are available at no cost from the GSFC DAAC in Maryland from new earth observing satellite instruments;

  - Pursue partnerships with operational and research agencies, such as NOAA and NASA, to facilitate the delivery of calibrated and validated products on water quality to managers and decision-makers;

- **Increase the Use of Landsat Imagery.** Acquisition of Landsat images (e.g., Enhanced Thematic Mapper (ETM) and finer scale commercial imagery) for the Bay watershed, and increased use of processed imagery for specific applications will improve our understanding of changes on several spatial and temporal scales.

  - Acquire Landsat ETM+ imagery consisting of 22 scenes for the Bay watershed at least every 2-3 years to analyze land cover in the context of C2K Agreement preservation clauses;

  - Facilitate the use of processed Landsat ETM+ imagery for a variety of specific applications, e.g., to quantify forest areas, riparian buffers, and nutrient inputs;

  - Selectively purchase commercial imagery of high resolution to augment coarser Landsat imagery to improve land cover characterizations for representative sites;

  - Improve and expand wetlands mapping: A variety of existing and new technologies can be used to examine and predict changes in wetlands. Both LIDAR altimetry and multi- and hyperspectral imaging should be pursued.

  - Improve mapping of tidal wetlands to include fine-scale topography essential to predict the future course of the wetlands;

  - Obtain higher resolution elevation data using LIDAR to improve predictions of the movement of water and solutes, particularly on local to regional scales where existing DEMs are too coarse;

  - Expand the use of multispectral and hyperspectral radiometry for assessing the health of wetlands.

Postscript

Since this workshop convened in Annapolis in early 2002, there has been significant movement towards developing water quality criteria for Chesapeake Bay. Despite this progress, data from *in-situ* and remote sensing are not used to an appreciable extent by managers to assess water quality. We are now poised to use these technologies to gauge compliance with recently established criteria and strongly urge the expanded use data and information from routine monitoring with those from new technologies.

Sea Grant

(stac) Scientific & Technical Advisory Committee
Chesapeake Bay Program

Present Status and Future Trends in Estuarine and Watershed Monitoring
Using Remote Sensing Technology
(Satellite, Airborne, *In-Situ*)

7–8 January 2002
Duke of Gloucester Room, Maryland Inn, 16 Church Circle, Annapolis, Maryland

Purpose: This two-day workshop highlights the present and future capabilities of remote sensing technology, including satellite, airborne, and *in-situ* sensors, to assess water quality and land-use changes in estuarine environments, with specific application to the regulatory responsibilities of the Chesapeake Bay Program. It centers on presentations by experts in three thematic areas, and on a round-table discussion between managers and scientists on specific data needs to address the 2000 Chesapeake Bay Agreement (C2K).

Rationale: The 2000 STAC review of the Chesapeake Bay Program's monitoring strategy recommended that the Program embrace remote sensing technologies to replace or supplement existing monitoring efforts for water quality parameters. The existing monitoring program is presently under review and will likely be revamped. This workshop will provide timely information on future technologies for land-use and water quality monitoring towards existing and new regulations in the C2K Agreement.

Agenda:

Day 1 – 7 January 2002 (Monday)

09:00   Welcome remarks and introductions – Jonathan Phinney, (ASLO and STAC) (since relocated)

Each panel will consist of three panelists who will each speak for 20-25 minutes with 5-10 minutes for questions. There will be 15 minutes at the end of each panel for summary statements, if needed. The moderator will provide a brief overview of the topic in addition to a presentation on a specific topic.

09:15 -10:45 Panel I – Observing water quality changes in bays and tributaries with *in-situ* sensors

Bill Boicourt, Moderator (Horn Point Laboratory, University of Maryland Center for Environmental Science)
Chuck Gallegos (Smithsonian Estuarine Research Center, Smithsonian Institution)
Mary Jane Perry (Darling Marine Center, University of Maine)
Rich Batiuk (Chesapeake Bay Program, US Environmental Protection Agency)

10:45 - 11:15 Break

11:15 - 12:45 Panel II – Detecting water quality changes remotely with airborne and satellite sensors

Larry Harding, Moderator (Maryland Sea Grant and Horn Point Laboratory, University of Maryland Center for Environmental Science)
Janet Campbell (Ocean Process Analysis Lab, University of New Hampshire)
Blanche Meeson (Goddard Space Flight Center, NASA) (temporarily relocated)
Rob Magnien (Dept. of Natural Resources, State of Maryland) (since relocated)

12:45 - 13:45 Lunch

13:45 - 15:15 Panel III– Detecting land-use changes with airborne and satellite sensors

Steve Prince, Moderator (Department of Geography, University of Maryland, College Park)
Tom Fisher (Horn Point Laboratory, University of Maryland Center for Environmental Science)
Jim Morris (Dept. of Biological Sciences, University of South Carolina)
Todd Schroeder (Canaan Valley Institute, West Virginia) (since relocated)

15:15 - 15:45 Break

15:45 - 17:00 General discussion and question-and-answer session

<div align="center">

Day 2 – 8 January 2002 (Tuesday)

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9:00 General discussion with all participants

The focus of the discussion is on how to integrate the existing sensor technologies into the C2K and other regulatory mandates from the management agencies.

Don Boesch, Moderator (University of Maryland Center for Environmental Science)

12:00–13:00 Lunch

13:00–15:00 Wrap-up discussion and summary

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